EIDE

Water Hammer in Pipes

Civil Engineering

B. S.

1904

WATER HAMMER IN PIPES

...BY...

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THESIS FOR THE DEGREE OF BACHELOR OF SCIENCE
IN CIVIL ENGINEERING

COLLEGE OF ENGINEERING
UNIVERSITY OF ILLINOIS

PRESENTED JUNE, 1904

May 27, 1904

This is to certify that the following thesis, prepared under the direction of Professor A. N. Talbot, Head of the Department of Municipal and Sanitary Engineering, by TORRIS EIDE, entitled WATER HAMMER IN PIPES, is accepted by me as fulfilling this part of the requirement for the degree of Bachelor of Science in Civil Engineering.

Ira O. Baker.

Head of the Department of Civil Engineering.

Water Hammer in Pipes.

The phenomenon of water hammer has without doubt been observed by nearly everyone, and it has received the attention of hydraulic engineers for many years. The excessive pressures developed by suddenly arresting the velocity of water flowing in pipes, must be provided for in water systems; and to find the laws governing these pressures, and the manner in which the impulse is transmitted has been the object of many investigations. These investigations, analytical and experimental, have added materially to our knowledge of the subject, so that the amount of pressure under given conditions may be calculated with considerable accuracy. Still, there are several phases of the phenomenon of more interest to the scientist than to the practical engineer, which are yet a matter of discussion.

It has been the object of the writer in his investigation to devise some method of experiment, which might add to the knowledge of the subject, and to state the results and conclusions of the experi-

ments conducted during the limited time at his disposal.

Existing Literature.

The literature on the subject of water hammer is rather meagre, and not altogether satisfactory. The discussions are often purely theoretical and are based upon wrong assumptions or involve erroneous principles. A few of the discussions, which appear to be in the right direction will be reviewed briefly. With one or two exceptions, only the conclusions reached will be stated.

In 1899, Mr. Elmer Church Smith of the University of Illinois wrote a thesis on the subject of water hammer. His experiments were numerous and extensive, and were conducted under differing conditions, as for example varying the length of pipe, the velocity of the water flowing in the pipe, and the speed of closing the valve. From his experiments, he arrived at the following conclusions:

1.- The pressure varies as the time of closing

the valve.

2.- The pressure varies directly as the velocity of the water flowing in the pipes.

3.- The pressure varies nearly as the square root of the distance from the valve.

4.- The pressure is independent of the diameter and length of the pipe.

Mr. Smith is deserving of much credit for the results obtained, as they are based upon numerous experiments, and as he was a pioneer in the investigation of water hammer.

Mr. Budd Willard Seymour wrote a thesis on the subject of water hammer in 1903 at the University of Illinois. Mr. Seymour not only supplemented and verified Mr. Smith's conclusions, but he also advanced our knowledge of this phenomenon, considerably. The following are the conclusions, which he drew from his experiments:

1.- The pressure created by the sudden closing of the valve is nearly proportional to the velocity of the water flowing in the pipe.

2.- The pressure is greatest at the valve and zero at the free end. It decreases not as the distance from the valve increases, but nearly as the

square root of the distance.

3.- The pressure is not one shock, but several successive shocks at decreasing intervals, the time of these intervals increasing as the length of the pipe, and as the velocity of the water.

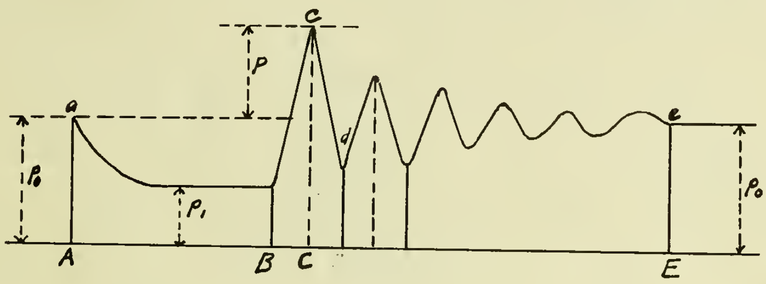
4.- The pressure does not occur simultaneously at all the points along the pipe, but is first felt at the valve, and this impulse travels along the pipe with a velocity of 4600 feet per second.

5.- The time that the compression lasts at any point is the time it takes the impulse to travel from that point to the free end and to return to the point in question.

6.- The computed time that the water continues to flow into the pipe after the valve is closed is not the same as the time it takes the impulse to travel from the valve to the free end.

Turneaure and Russell's "Public Water Supply" page 243 gives the formula $p = \frac{v E_w}{V}$, where p equals the pressure in pounds per square inch, v = the velocity of the water in the pipe. V = the velocity of sound in water = 4700 feet. E_w = modulus of elasticity of water = 300,000. No derivation was given for this formula.

Prof. M. Merriman in the eighth revised edition of his "Treatise on Hydraulics page. gives the following theoretical discussion of the subject of water hammer.



p_0 = static unit pressure with no flow.

p_1 = static unit pressure under flow.

Let $P = Cc - Ee$ excess of maximum dynamic unit pressure over unit static pressure with no flow. This excess is due to the water hammer, and its value is to be found. $p_0 + p - p_1$ = actual dynamic unit pressure due to the retardation of the velocity. The dynamic pressure on an area $\underline{a} = (p + p_0 - p_1)\,a$; represent this by P_1. If the pressure is regarded as varying uniformly from 0 to P during the time t in which the valve closes, its mean value is $\frac{1}{2}P$, and its total impulse during the time t is $\frac{1}{2}Pt$. If l is the length of the pipe, w the weight of a cubic unit of water and v the velocity of flow, the total

weight of water is wal, and its impulse is $wal \frac{v}{g}$.

Equating, $\frac{1}{2} P t = wal \, v/g$. $P = 2 \, wal \, v/gt$.

$$p_0 + p - p_1 = 2 \, wal \, v/gt$$

$$p = 2 \frac{walv}{gt} + p_1 - p_0 \quad (1).$$ excess dynamic pressure in t.

The disturbance is propagated through the water with a velocity of about 4670 ft. per second. Let this be represented by u. In a pipe of length l with an open valve at the end, let the velocity of the water be v. Then the time $\frac{l}{u}$ must elapse after the valve closes before the velocity begins to be check- at the upper end of the pipe, and the further time of l/u must elapse before the pressure due to this retardation can be transmitted back to the valve. The total time $2 \, l/u$ must elapse before the gauge at the valve can indicate the pressure due to the retardation of the velocity in the length l. Hence, if the time in which the valve closes be equal to or less than $2 \, l/u$, the time t in the above formula is to be replaced by $2l/u$ and thus, $p = \frac{wu}{g} v + p_1 - p_0$ (2). is the maximum excess of dynamic unit pressure that can ever occur in the pipe. This pressure depends upon the velocity of the water and upon the initial and final static pressures.

When water is in motion, the kinetic energy in a length δl at the gauge is $w a l \frac{v^2}{2g}$; when it is brought to rest under a unit stress $\underline{s}$, its stress energy is $a \delta l \cdot \frac{s^2}{2E}$, if E be the modulus of elasticity of the water. Equating these expressions and substituting $p + p_0 - p_1$ for $\underline{s}$

$$p = \left(\frac{E w}{g}\right)^{1/2} v + p_1 - p_0$$

replacing E by $\frac{w u^2}{g}$ formula (2) is obtained.

When $\underline{v}$ is in feet per second and p_0, p_1 and p in pounds per square inch, these formulas become

$$p = 0.027\left(\frac{l}{t}\right) v + p_1 - p_0. \qquad p = 63 v + p_1 - p_0.$$

The first is to be used when t is greater than $0.000428\, l$, and the second when $\underline{t}$ is equal to or less than $0.000428\, l$, $\underline{l}$ being in feet.

Prof. N. Joukowsky of the Imperial University of Moscow presented in 1898 to the Imperial Academy of Science at St. Petersburg, a very complete discussion of the phenomenon of water hammer. This discussion is based upon a very extensive series of experiments at the Moscow waterworks. The following are the conclusions at which he arrived:

1.– The hydraulic shock is propagated along the pipe with a constant velocity, whose

magnitude is not dependent upon the force of the shock. This velocity depends upon the material of the pipe, and the ratio of the thickness of the pipe to its diameter.

2.- The hydraulic shock is propagated through the pipe with uniform force. Its intensity is proportional to the velocity lost by the water, and to the velocity with which the shock is propagated in the pipe.

3.- The appearance of periodic oscillations in the pressure in the water-pipe is completely explained by the reflection of the shock wave at the end of the pipe.

4.- The motion of the water as a body has no noticeable influence on the shock; the latter is determined only by the lost velocity.

5.- A very large increase in pressure occurs upon the transition of the shock wave from a pipe of large diameter to one of smaller diameter.

Theory of Water Hammer.

Referring to Prof. Merriman's discussion on page 5, it will be noticed that he first considers the water as a body, and later he considers only a differential, showing that the value of p resulting from the two equations is the same. Experiments show that the pressure is independent of the length of the pipe, and it would, therefore, seem logical to base a theoretical discussion upon a differential length instead of upon the water as a body.

The theory of water hammer presented here, is as given by Prof. A. N. Talbot. Suddenly arresting the flow of water in a pipe, causes the water near the valve to be compressed a certain amount, while at the free end there is no compression. Neglecting the distention of the pipe at present; let dx equal the length of a column of water whose cross-section is 1 square foot, let P equal the pressure at the valve on 1 square inch generated by the sudden stoppage of the water, then the pressure on 1 square foot equals $144P$. The weight of a column of water 1 square foot cross-section and dx long equals $w.dx$,

if w equals the weight of a cubic foot of water.
Flowing with a velocity V, the energy in this water is equal to $\frac{1}{2} MV^2$. This becomes $\frac{1}{2} \frac{w\,dx}{g} V^2$, since $M = \frac{w\,dx}{g}$. Let λ equal the amount this dx length of water is compressed at the valve. Since λ is proportional to the unit stress, $\lambda = \frac{Sl}{E}$, where $S = P$, l = length of the column of water $= dx$, and E = the modulus of elasticity of water. $E = 300{,}000$ is used here, and what error there is in this will not appreciably affect the result. If dx is expressed in feet, the product is in foot pounds.
The work done is equal to the average pressure multiplied by the distance moved through. Since the pressure increases from 0 to $144P$, the average pressure equals $\frac{144P}{2}$. The work done is equal to $\frac{144P}{2}\lambda$ or $\frac{144P}{2} \times \frac{P\,dx}{E}$. The work done is also equal to the energy in the water $\therefore \frac{144P}{2} \times \frac{P\,dx}{E} = \frac{1}{2} \frac{w\,dx}{g} V^2$, $P^2 = \frac{wE}{144g} V^2$, $P = \sqrt{\frac{wE}{144g}}\, V$. Substituting the numerical values for w, E, and g, we have $P = 63.6\,V$. This is the value for the pressure at the valve generated by the sudden stoppage of the water, when the elasticity of the metal is not taken into account.

Considering the elasticity of the metal in

the pipe, the deformation λ_2 of the pipe $= \frac{\pi d S}{E'}$. and $Pd = 2tS$, $S = \frac{Pd}{2t}$, where P = the pressure per unit area, d = the diameter of the pipe, t = the thickness of the pipe, and S = the tensile stress of the metal in the pipe in pounds per square inch, E' = the modulus of elasticity of the metal $= 30{,}000{,}000$. Then $\lambda_2 = \frac{\pi d^2 P}{2tE'}$. The total lateral pressure F_2 in the pipe $= \frac{Pd}{2}\,dx$. for a length dx. The work done in expanding the pipe $= \frac{1}{2} F_2 \lambda_2 = \frac{1}{2} \cdot \frac{Pd}{2} \cdot dx \cdot \frac{\pi d^2 P}{2tE'} = \frac{1}{8} \cdot \frac{\pi P^2 d^3}{tE'} \cdot dx$. Work done in compressing the water $= \frac{1}{2} F_1 \lambda_1 =$ $\frac{1}{2} \cdot \frac{\pi^2 d^2}{4} \times \frac{P^2}{E}\,dx = \frac{1}{8}\,\frac{\pi P^2 d^2}{E}\,dx$. Energy of the water $= \frac{1}{2} \cdot \frac{w}{g} \cdot \frac{\pi d^2}{4} \cdot dx \cdot V^2$. Equating energy to work done we have $\frac{1}{8}\,\frac{w \pi d^2}{g} \cdot dx \cdot V^2 = \frac{1}{8}\,\frac{\pi P^2 d^3}{E'}\,dx + \frac{1}{8}\,\frac{\pi d^2 P^2}{tE} \cdot dx$, reducing, $\frac{w}{g} E V^2 = 1 + \frac{Ed}{E't} P^2$, $P^2 = \frac{1}{1+\frac{Ed}{E't}} \cdot \frac{wEV^2}{g}$, $P = \frac{1}{\sqrt{1+\frac{Ed}{E't}}} \cdot \sqrt{\frac{wE}{g}}\,V$ pressure per unit area expressed in homogeneous units. Expressing P in pounds per square inch and V in feet per second, this reduces to $P = \frac{1}{\sqrt{1+\frac{Ed}{E't}}} \cdot \sqrt{\frac{wE}{144g}}\,V$. The form of this formula is the same as the one when the elasticity of the pipe was neglected, the constant $\frac{1}{\sqrt{1+\frac{Ed}{E't}}}$ depending upon the size and the thickness of the pipe, being the only difference. Using $d = 2.06$ inches, and $t = .154$ inches, the values

for the pipe used by the writer, the formula gives $P = \frac{1}{\sqrt{1+\frac{2}{3}}} \cdot 63.6\,V$ or $P = 59.7\,V$.

General Description of Experiments.

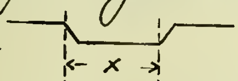
In the experimental work of the writer, two distinct lines of experiments were followed. In previous experiments made by other experimenters only one valve was used in producing the water hammer. It occurred to the writer that the behavior of the water hammer might be better studied, if two valves were used, one at the outlet, and the other at say half the distance to the source of supply. These two valves were arranged so that they might be closed simultaneously, or the second valve at some determined interval after the first. By this method of operation, it was hoped to so confine or intercept the impulse as to ascertain wherein lay the cause of the decrease in pressure, as the impulse was propagated towards the source of supply.

In the second method of experimenting, suggested by Dr. F. R. Watson of the University of

Illinois, the hammer was produced by striking a plunger with a pendulum. The drop of the pendulum was varied, and a valve at the free end of the pipe was open in some experiments and closed in others. The object of these experiments was to compare the pressures produced by the impact of the water in motion, and the impact of a body upon the water at rest.

Apparatus.

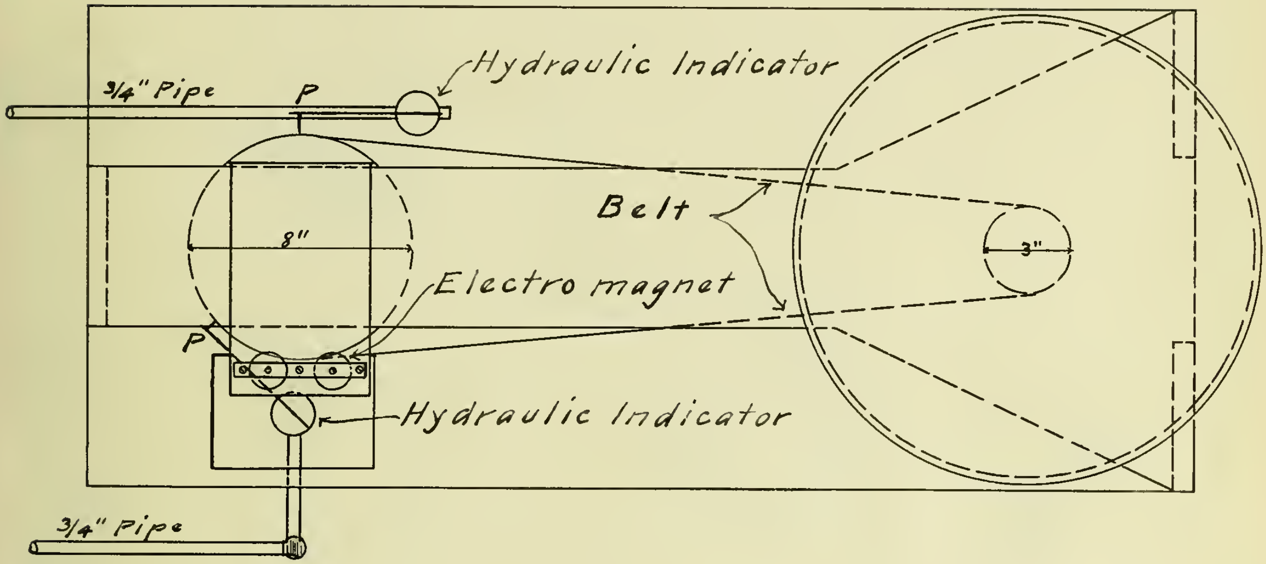
A standpipe 60 feet high furnished the water used in these experiments. The velocity of the water flowing through the pipe system was regulated partly by a valve at the standpipe, and partly by the head in the standpipe. In determining this velocity, the water was run into a tank for 1 minute, and then weighed; the area of the pipe being known, the velocity was readily obtained by the formula $V = \frac{Q}{A}$. The pipe used in these experiments was 2 3/32 inches in diameter. Several air vents were placed along the pipe. Two Crosby hydraulic indicators were used

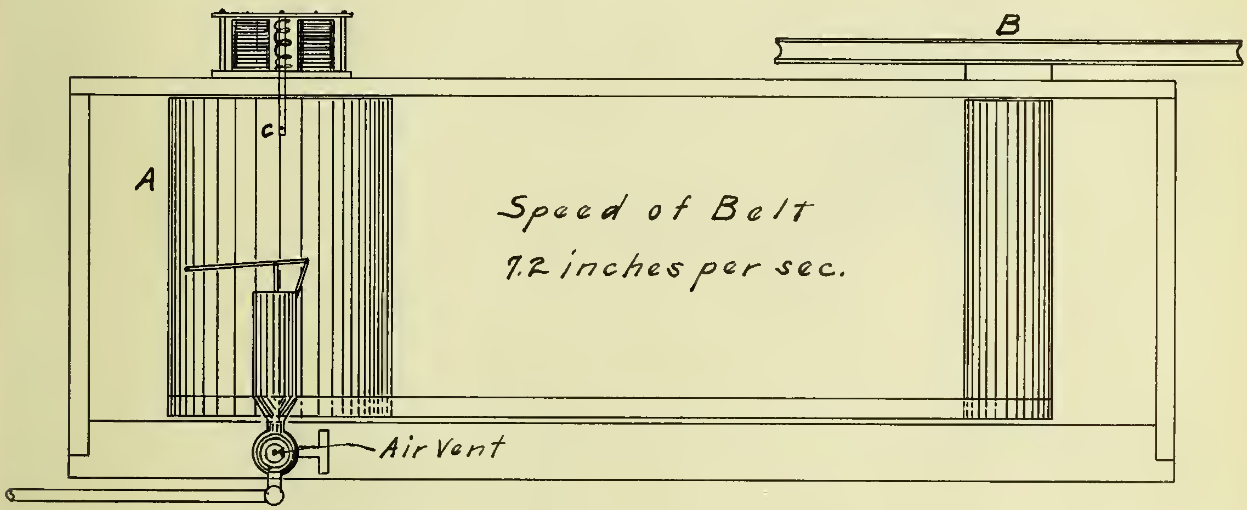
in measuring the pressures, the 200 pound and the 480 pound to the inch spring being used as the conditions required. The sketch on page 15 shows the arrangement and plan of the recording device. The pressures are recorded by the pencils (P) on a sheet of paper wrapped around the 8-inch drum (A) and fastened with thumb-tacks. A belt of cotton webbing, running at a speed of 7.2 inches per second drives this drum. The belt is in turn driven by a rope drive running over an 18-inch pulley (B) to an electric motor, which runs at a uniform speed. The time of closing the valve is recorded by a pencil (c) marking on the sheet around the drum (A). This pencil is fastened to an electro-magnet so that when the valve begins to close an electric connection is made and the pencil is brought down by the magnet; when the connection is broken, the armature is pushed back by a spring, thus raising the pencil. A line like figure 

is made by the pencil. The distance x is the time in which the valve is closed.

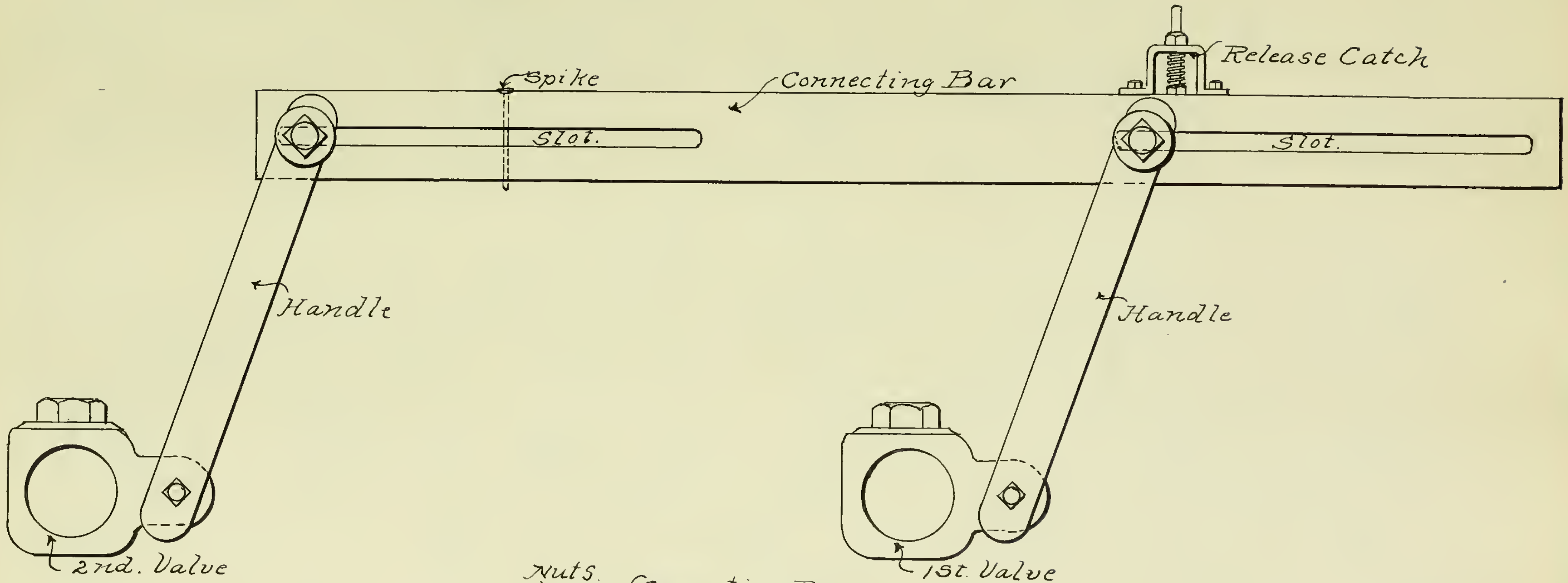
The arrangement for closing the two valves in the first set of experiments is shown on page 16. The two valves were placed opposite

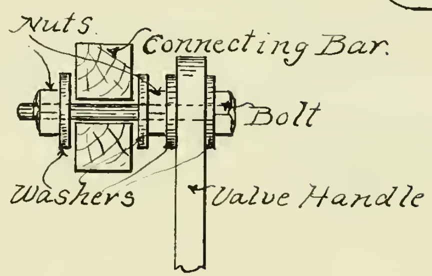
SKETCH
SHOWING
RECORING DEVICE.





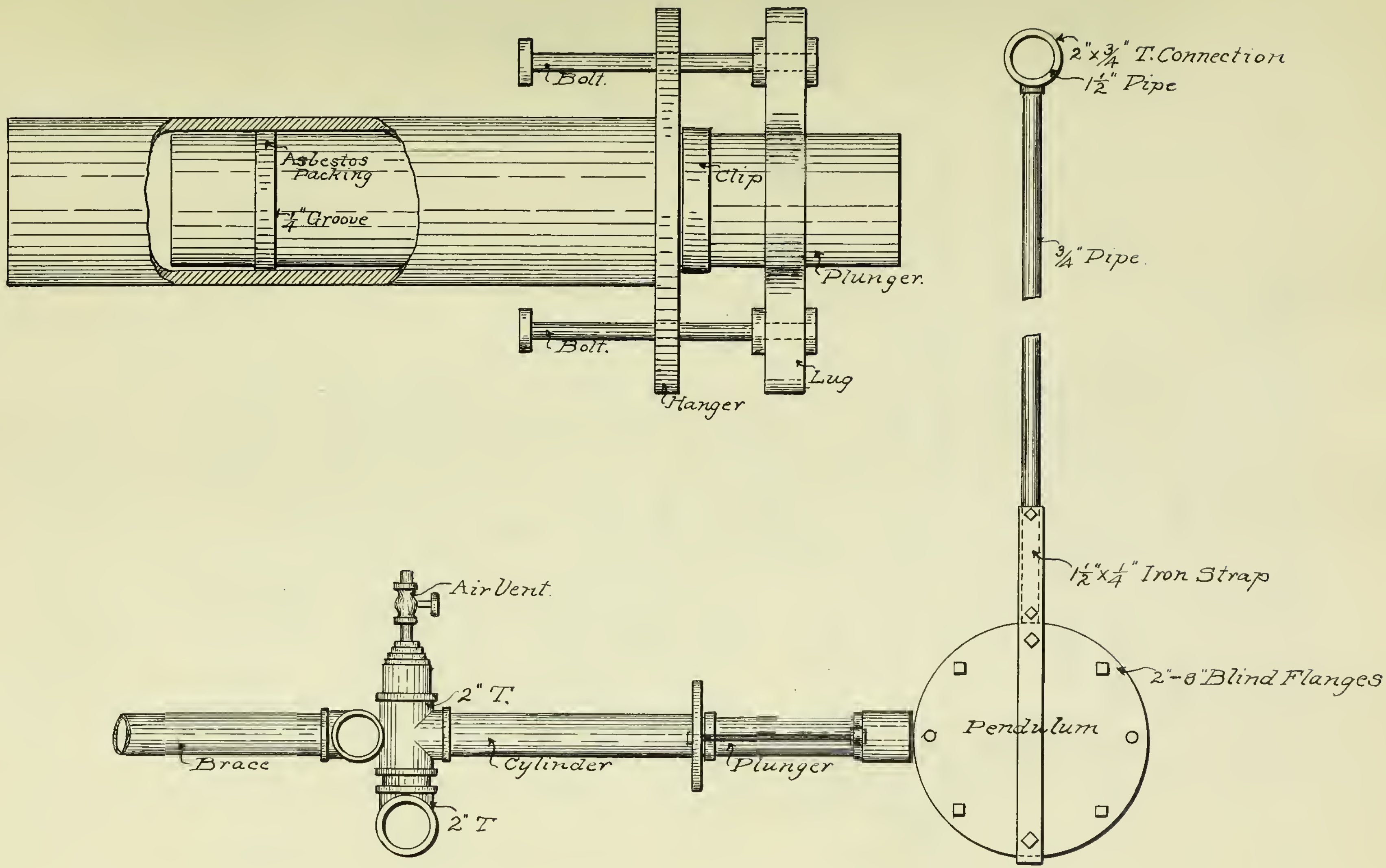
DEVICE FOR
CLOSING VALVE





each other, and 180 feet apart on the pipe line. Into an opening near the top of each valve handle, a ½ inch bolt was firmly fastened. These bolts worked in the slots of the connecting bar, and the nuts securing the bolts in the slots were turned up loosely so as to prevent binding. For simultaneous closing, a spike was inserted behind each bolt, but for closing the second valve later than the first, the arrangement was as shown. Both valves being open, the bolts were at the ends of the slots. The first was held in place by a release catch, which released the bolt when the valve was closed, while the second bolt was free and slid in the slot until it engaged with a spike at the required point, thus closing the second valve.

The sketch on page 18 shows the design of the plunger, and the arrangement of the apparatus for the second set of experiments. A 2-inch iron pipe, 15 inches long was bored out smooth; and a cast iron plunger was turned to fit this cylinder. A groove ¼ inch deep was cut near the end of the plunger and filled with asbestos packing soaked in oil, in order to pre-

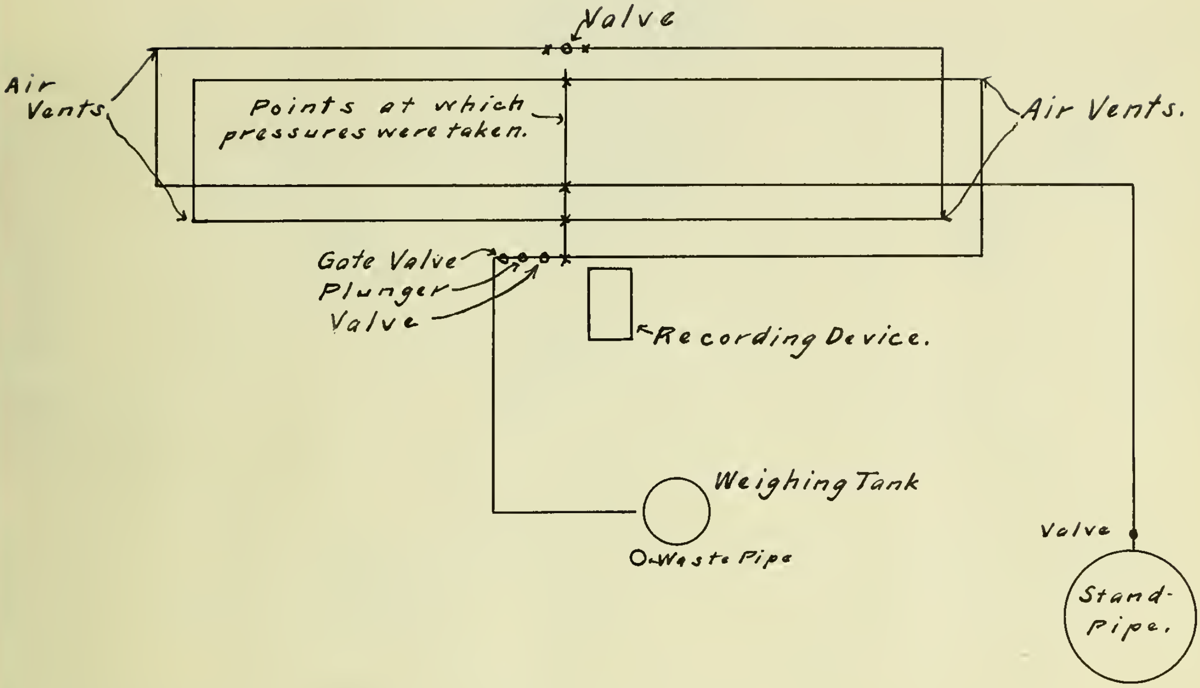


PENDULUM AND PLUNGER.

vent leakage. Fastened to the lugs on the plunger, and passing through a flange screwed on the cylinder, were two bolts to prevent the plunger from being forced out by the water-pressure. The metal clip shown, clasped the plunger tightly enough so as to remain in any position. Its object was to record the distance, which the plunger was driven in, and so the compression. The second figure shows the method of connecting the cylinder to the pipe system.

The pendulum consisted of 2-8 inch blind flanges securely bolted together. The suspension rod, a 3/4 inch pipe, was rigidly secured to the flanges by means of two iron straps. A 2 inch by 3/4 inch "T" was screwed to the upper end of the suspension rod, and slipped over a pipe supported by two roof trusses. The bob of the pendulum was just in contact with the plunger, when hanging vertically. The two flanges, including straps and bolts, weighed 94 pounds, and the suspension rod weighed 12 pounds.

Layout of the Pipe.



The points at which pressures were taken were 60 feet apart. The connection between the 2 inch pipe and the indicators was made with a 3/4" inch pipe varying in length from 1½ feet to four feet, and arranged with swing joints so that the jar in the pipe would not be communicated to the indicators. The gate valve was closed whenever experiments were made with the plunger.

Simultaneous Closure of Valves.

The valves were in these experiments closed simultaneously by means of the connecting bar described on page 17. The pressures along the pipe are shown on plate 1. The curve for the velocity of 5 feet per second is probably the most characteristic of the three curves. However, in each case, it will be noticed that there is a decided increase in pressure on the far side of the second valve, while between the two valves, the pressure decreases towards the second valve. Comparing the maximum pressures with the pressure found by the formula $P=57V$, it is found that the pressure between the two valves falls below this value, and except for the velocity of 7 feet, it is exceeded beyond the second valve. In no case is there more than two pulsations between the valves, and in general, the secondary impulse is most evident at the two valves. The average interval is .22 second, and it does not seem to vary with the velocity. The form of curve between the two valves can be due only to the conditions under which the hammer is produced. As no water flows into this section of pipe after closing the valves,

there is a tendency to form a vacuum, and so reduce the effect of the hammer. P = 48 V gives the pressure at the first valve.

Beyond the second valve the hammer acts as under ordinary conditions, except for the excessive pressure. This pressure is uniform until within about 40 feet of the standpipe, when it drops off very rapidly. No explanation of this increase of pressure has been found. P = 63 V gives the pressures on the far side of the second valve. As might be expected, the duration of the compression was short, due to the short length of pipe, 120 feet. The interval between the pulsations decreased as the number of impulses increased, as many as seven being noticed. The following tables give the time intervals and the pressures for the impulses beyond the second valve.

180(b) V = 3 ft.

Pulsations	Pressure in lbs. per sq. in.	Time between Pulsations in Seconds.
1	190	
		.42
2	130	
		.30
3	85	
		.22
4	60	
		.21
5	45	

240 V = 3 ft.

Pulsations	Pressure in lbs. per sq. in.	Time between pulsations in Seconds
1	180	
		.44
2	145	
		.36
3	110	
		.29
4	60	
		.26
5	35	

180(b) V = 5 ft.

Pulsations	Pressure in lbs. per sq. in	Time between Pulsations in seconds
1	315	.47
2	175	.33
3	145	.25
4	85	.21
5	65	.18
6	50	

240 V = 5 ft.

Pulsations	Pressure in lbs. per sq. in.	Time between Pulsations in seconds.
1	315	.47
2	250	.39
3	185	.32
4	135	.27
5	70	.23
6	45	

It will be seen from these tables that the interval between successive pulsations increases with an increase in the velocity. The time interval is also greater for the 240-foot point than for the 180-foot point.

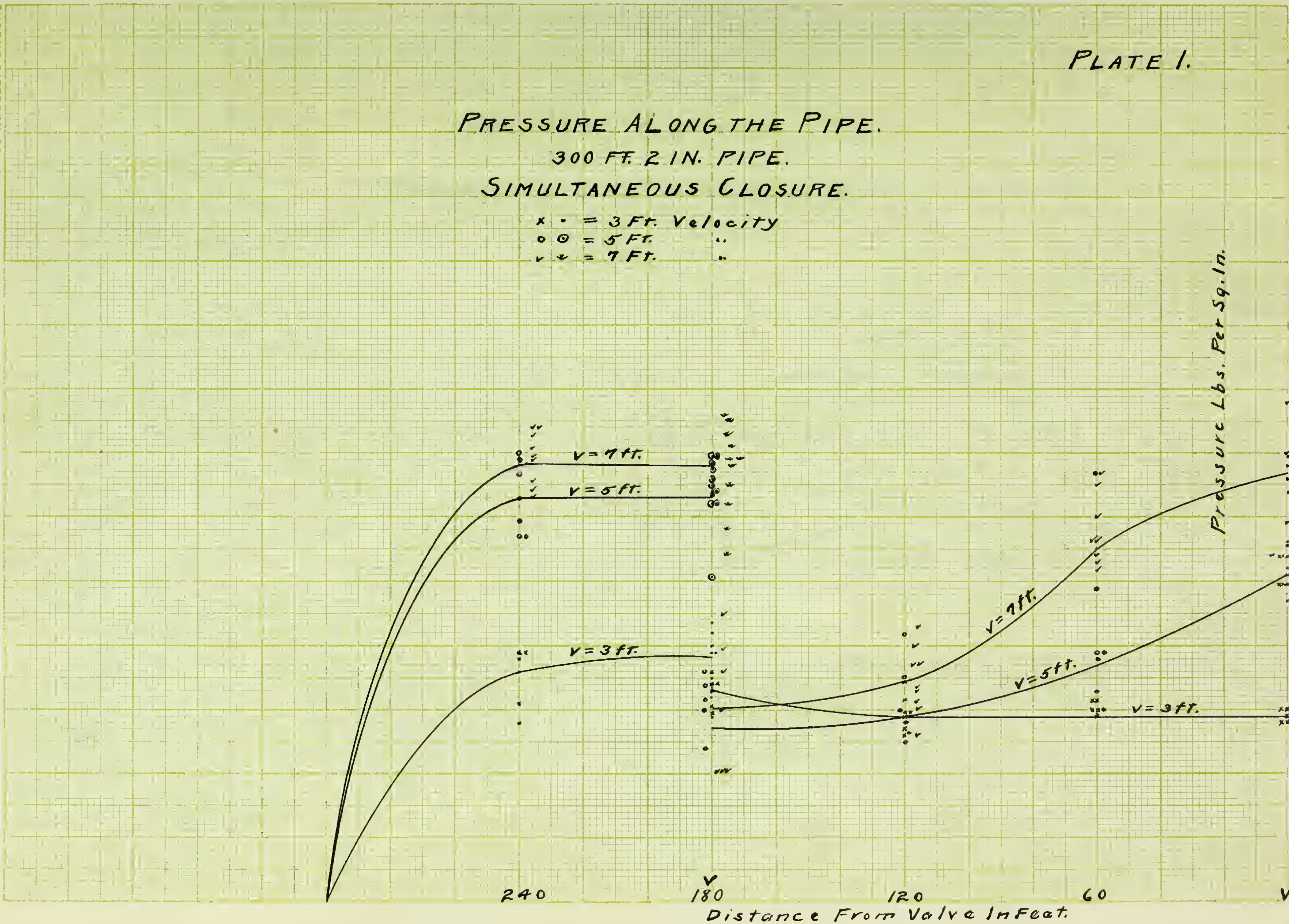


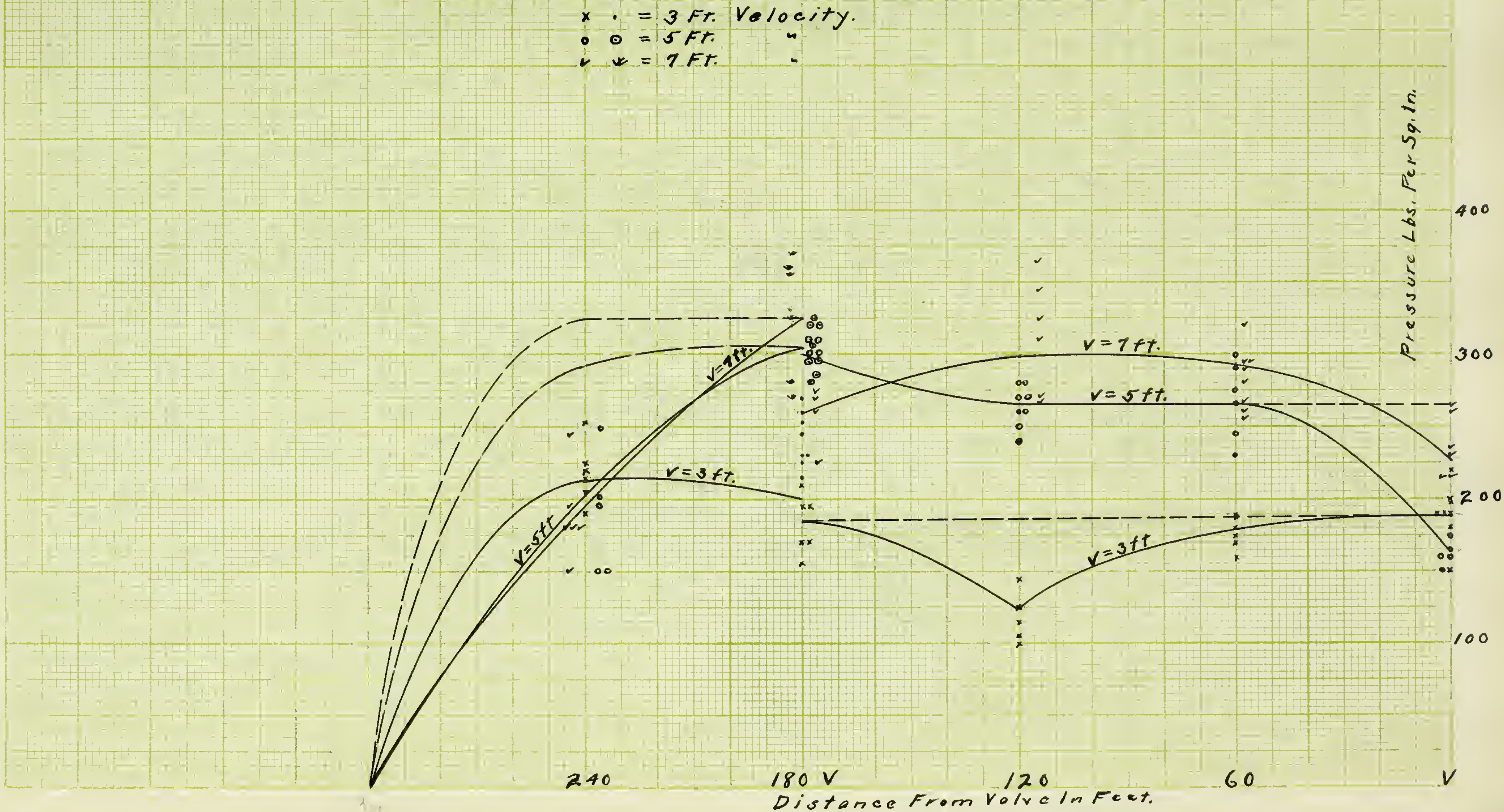
PLATE I.
PRESSURE ALONG THE PIPE.
300 FT. 2 IN. PIPE.
SIMULTANEOUS CLOSURE.
x • = 3 Ft. Velocity
o ⊙ = 5 Ft. "
v ✓ = 7 Ft. "
v = 7 ft.
v = 5 ft.
v = 3 ft.
Pressure Lbs. Per Sq. In.
400
300
200
100
240
180
120
60
V
Distance From Valve In Feet.

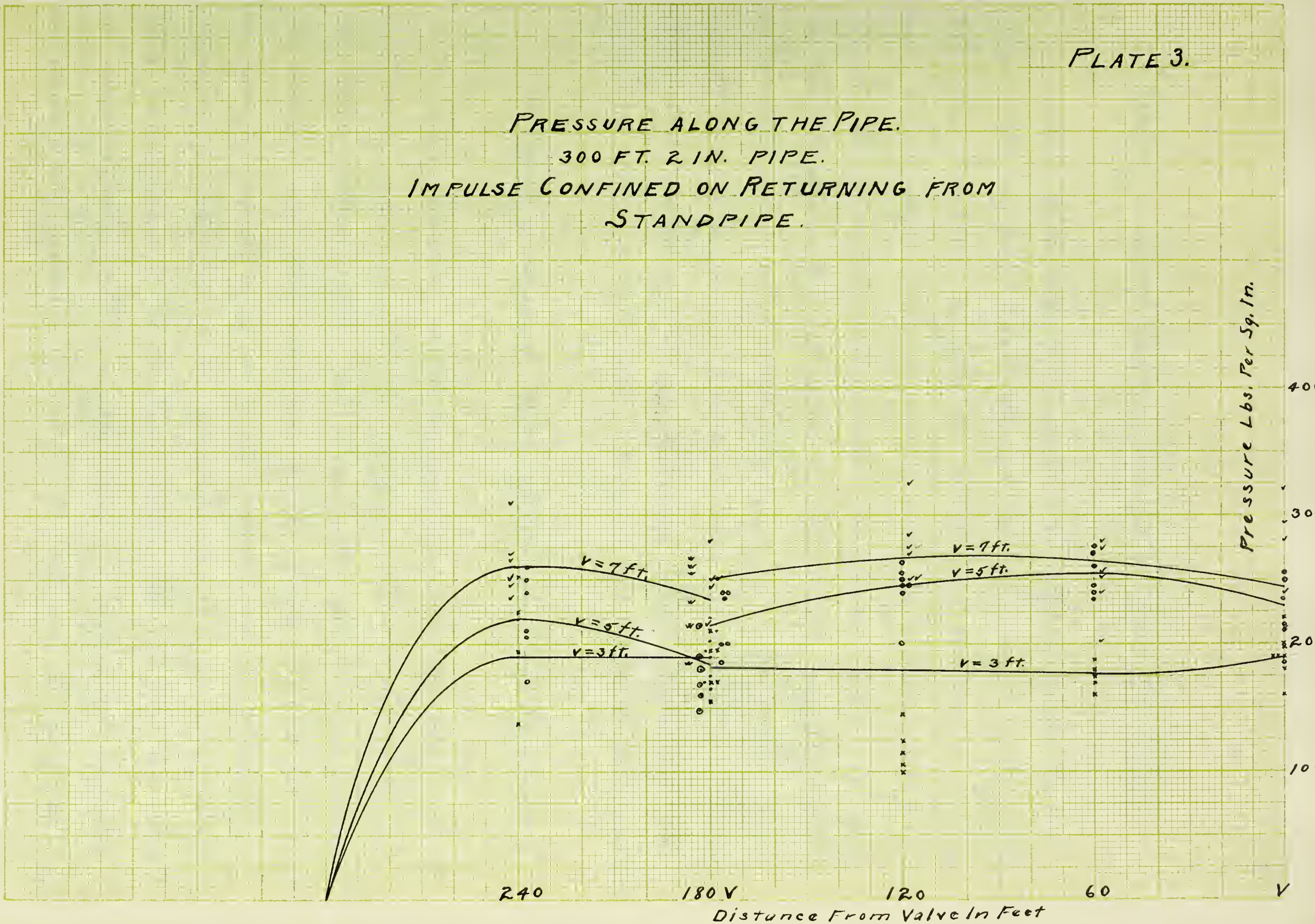
PLATE 2.

PRESSURE ALONG THE PIPE.

300 FT. 2 IN. PIPE.

CLOSING SECOND VALVE AFTER IMPULSE HAS PASSED.





EUGENE DIETZGEN CO. CHICAGO.

Closing Two Valves, One Later than the Other.

In these experiments, the object was to so close the valves that the impulse originating from the first valve might be intercepted and confined. The experiments were not very successful, and the results were not uniform, due chiefly to the difficulty of closing the valves rightly. However, the curves for the pressures along the pipe will serve to give a general idea of what is to be expected. Nothing more than a description of the curves and indicator diagrams will be attempted.

1. Closing Second Valve after Impulse Has Passed.

This series is the most unsatisfactory of all. It was attempted to confine the water between the two valves, after the impulse had compressed the water in that section of the pipe. With the water so compressed, one would expect an indicator diagram showing a sustained pressure, and this was found to be true when the valves worked successfully. It might also be expected to find a nearly uniform pressure between the two valves.

The curves, however, do not for some reason show this uniformity. Turning to the curves on plate 2, it will be seen that there is a small increase in pressure on the far side of the second valve. Except for the velocity of 3 feet, the pressures decrease almost in a straight line from the second valve to the standpipe. The writer believes that the curves to be correct should follow more nearly the dashed lines shown. The irregularities appearing at different points in the curves between the two valves must be due to the changing distribution of air in the pipe.

2. Closing Second Valve So as to Confine Impulse on Return from Standpipe.

The second valve was closed from .11 to .164 seconds after the first valve. This allowed the impulse time enough to travel to the standpipe and at least past the second valve on its return to the first valve. The pressures were the same in nearly every case, whether the second valve was closed after the impulse returning from the standpipe had passed, or it was given time to reach the first valve and start back. The only difference noticed was in the form of

the indicator diagram. Generally, for the second case, it was sustained, while for the first case though sustained for a short time, it descended rapidly to the base line. No explanation can be given for the sustained pressures in this case. The curves on plate 3 show a nearly uniform pressure with a small increase near the mid-point. Beyond the second valve, there is a slight decrease in pressure, but at the 240-foot point, the pressure has reached almost the highest indicated between the valves, and from there the pressure decreases rapidly. The pressures do not have a fixed ratio to the velocity, but are proportionally smaller for an increase in velocity, Whether or not, this decrease was due to the method of producing the hammer could not be ascertained. The pulsations beyond the second valve occur a decreasing intervals.

Indicator Diagrams

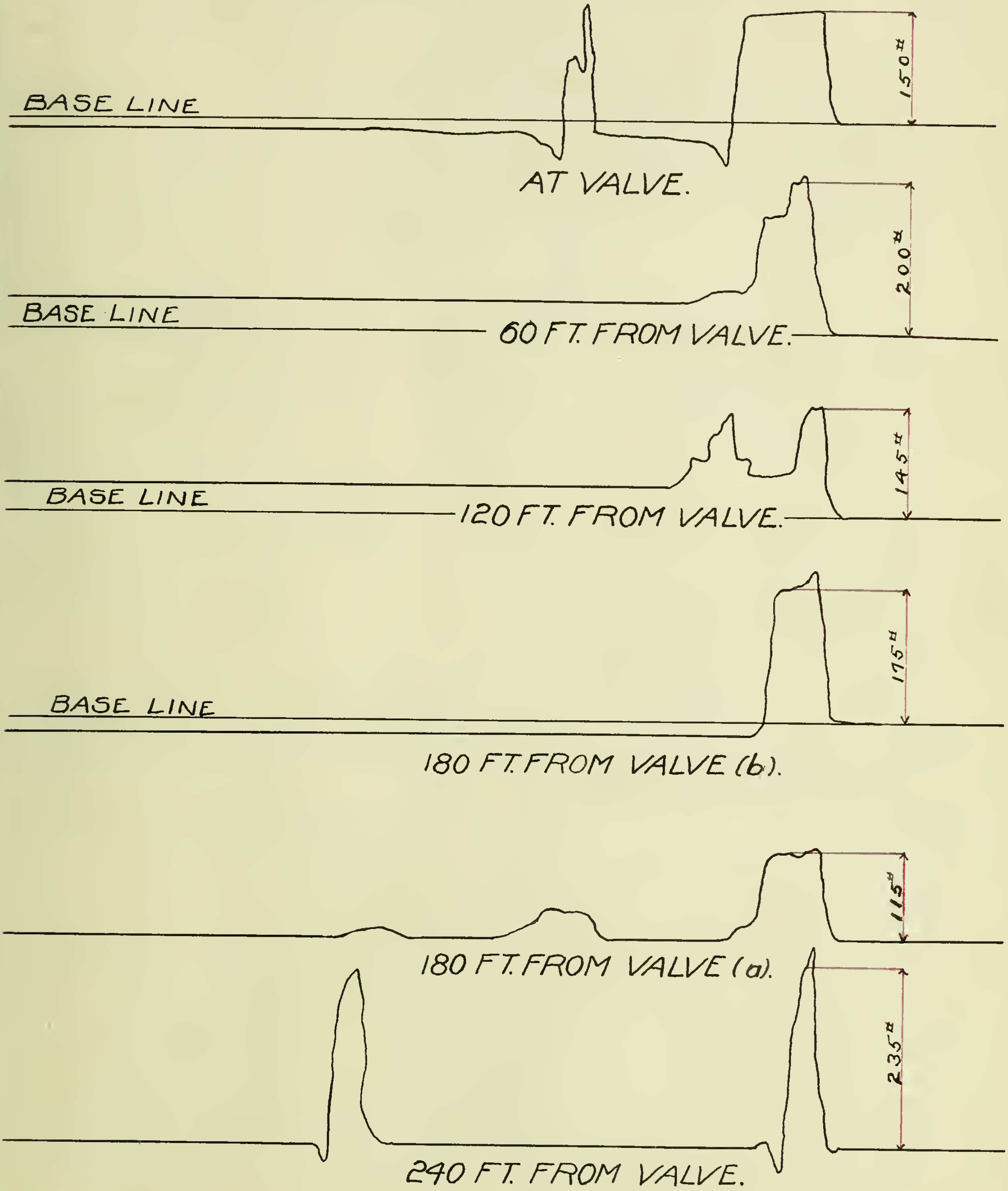
The following diagrams on pages 27 to 37 show the general character of the indicator diagrams. The digrams on pages 32 to 35 are not all representative of sustained pressures, as the conditions for sustained pressures could not be obtained for all the points along the pipe.

DIAGRAM

SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 3 FT. PER. SEC.

SIMULTANEOUS CLOSURE.

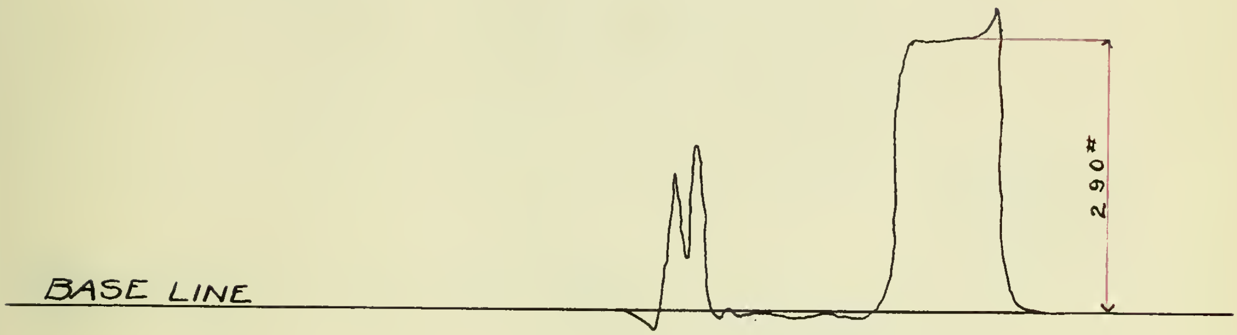


DIAGRAM

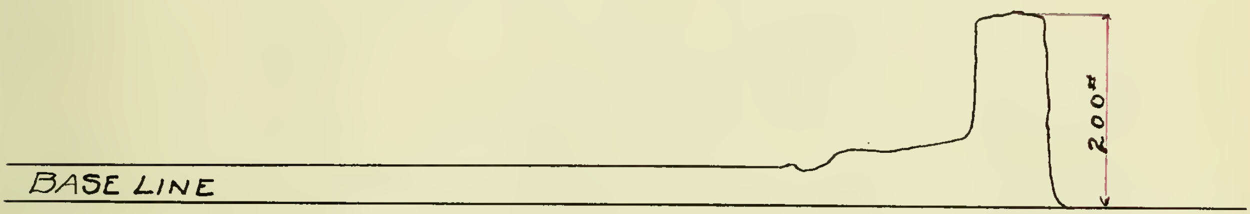
SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 5 FT. PER SEC.

SIMULTANEOUS CLOSURE.



AT VALVE



60 FT. FROM VALVE

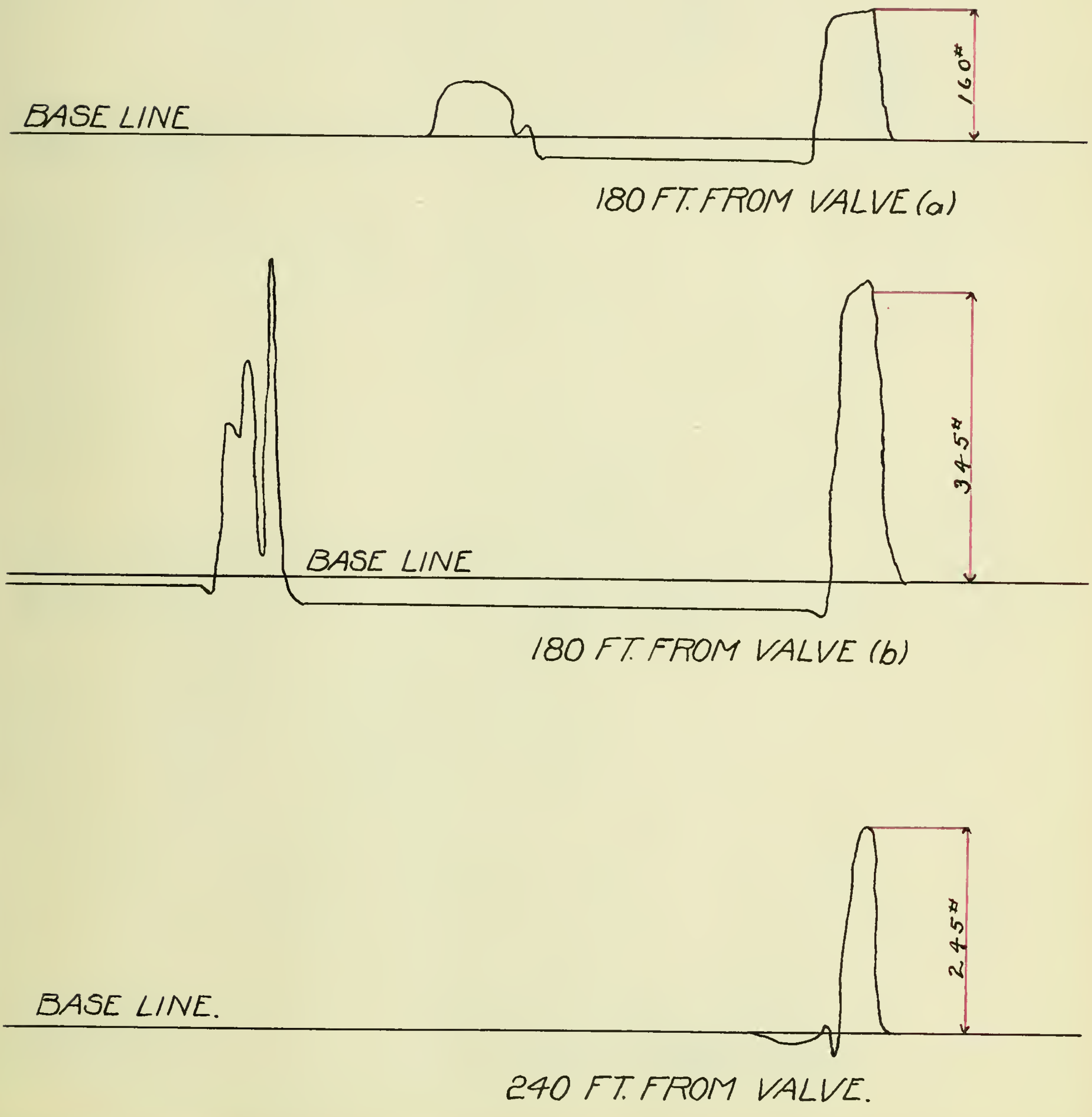
120 FT. FROM VALVE.

DIAGRAM

SHOWING PULSATIONS.

300 FT. PIPE VELOCITY = 5 FT. PER SEC.

SIMULTANEOUS CLOSURE.

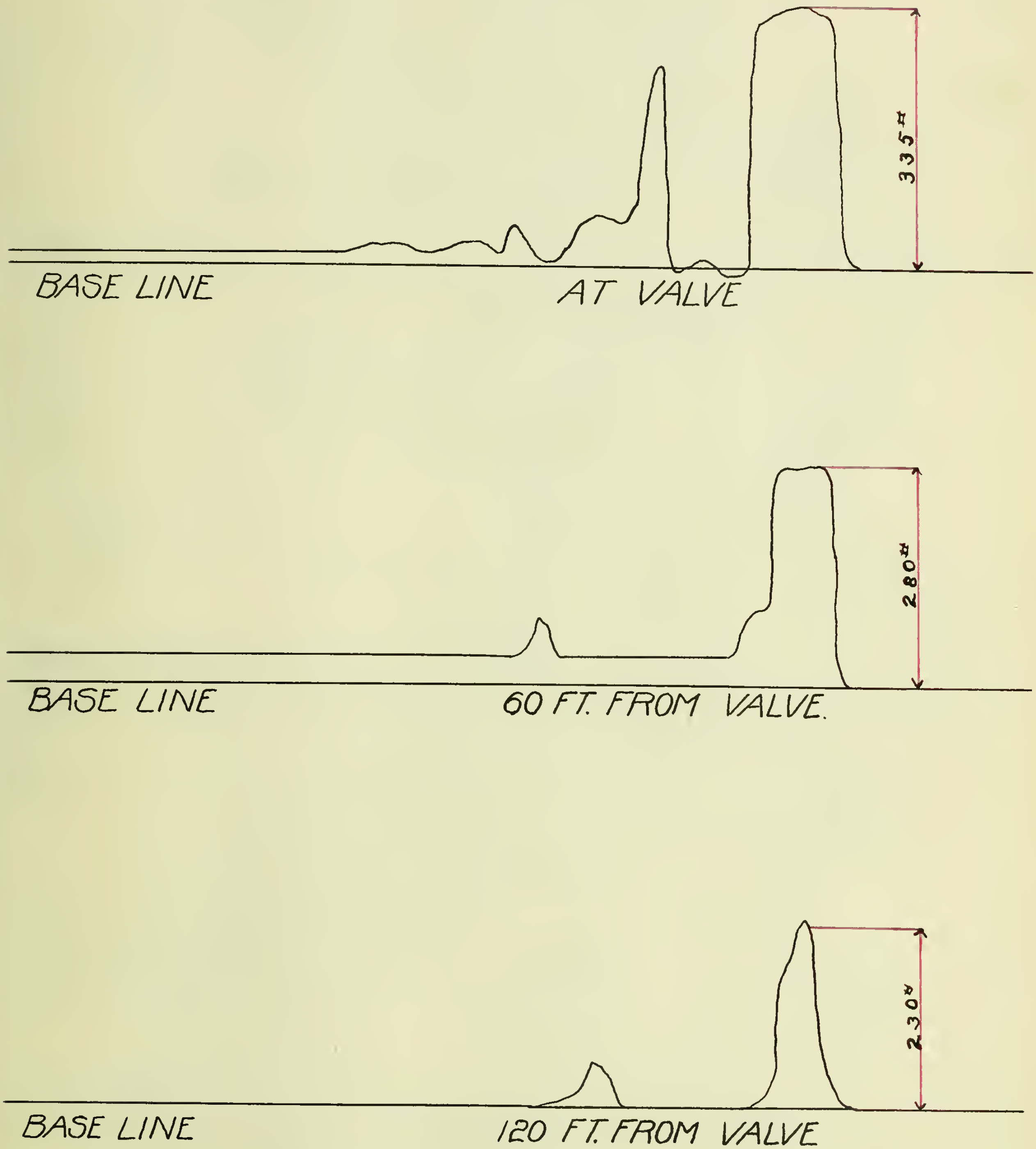


DIAGRAM

SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 7 FT. PER SEC.

SIMUTANEOUS CLOSURE.

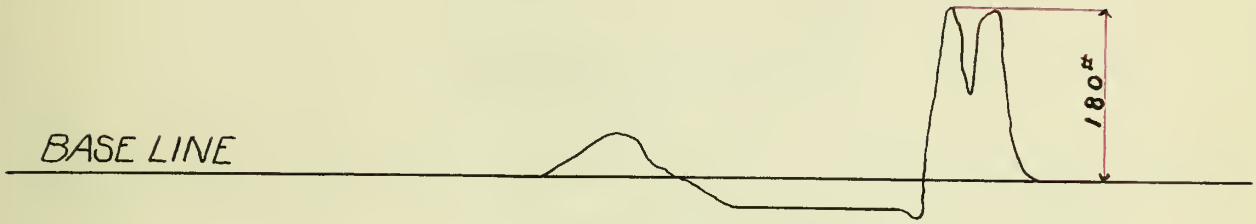


DIAGRAM

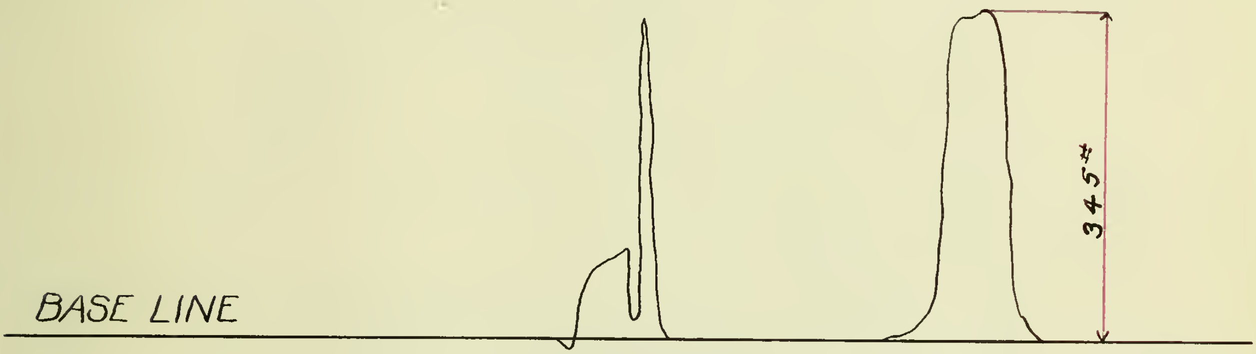
SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 7 FT. PER SEC.

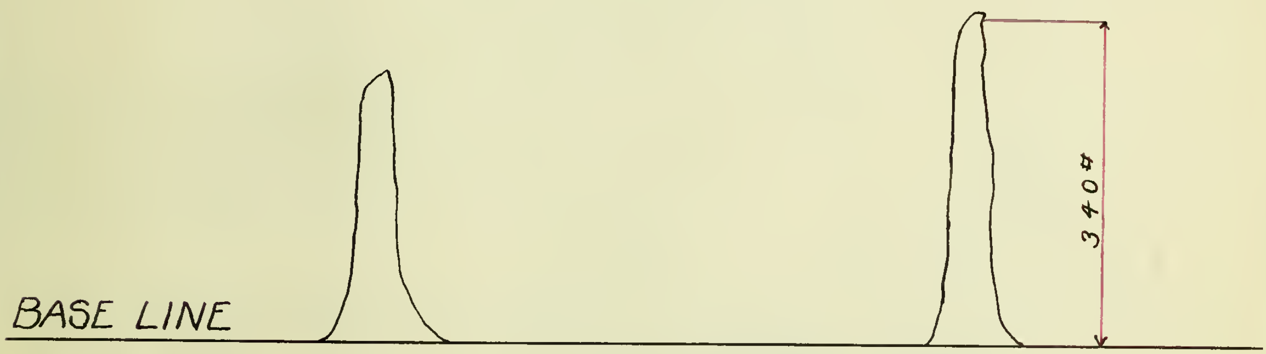
SIMULTANEOUS CLOSURE.



180 FT. FROM VALVE (a)



180 FT. FROM VALVE (b)



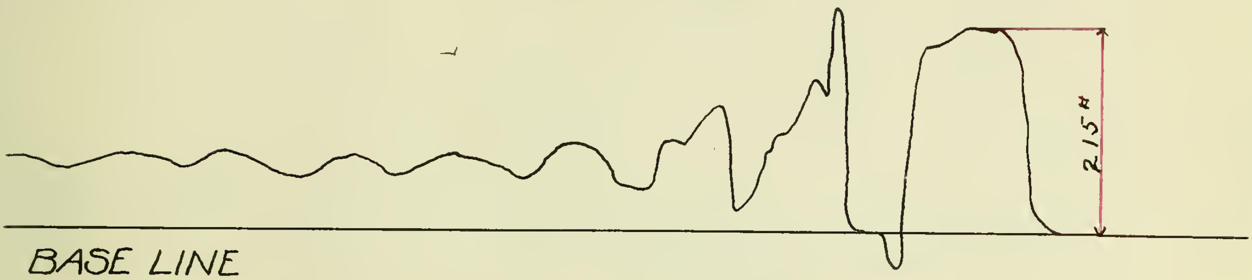
240 FT. FROM VALVE

DIAGRAM

SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 3 FT PER SEC.

CLOSURE AFTER IMPULSE PASSES 2ND. VALVE.



BASE LINE

AT VALVE.

BASE LINE 60 FT. FROM VALVE.

BASE LINE 120 FT. FROM VALVE.

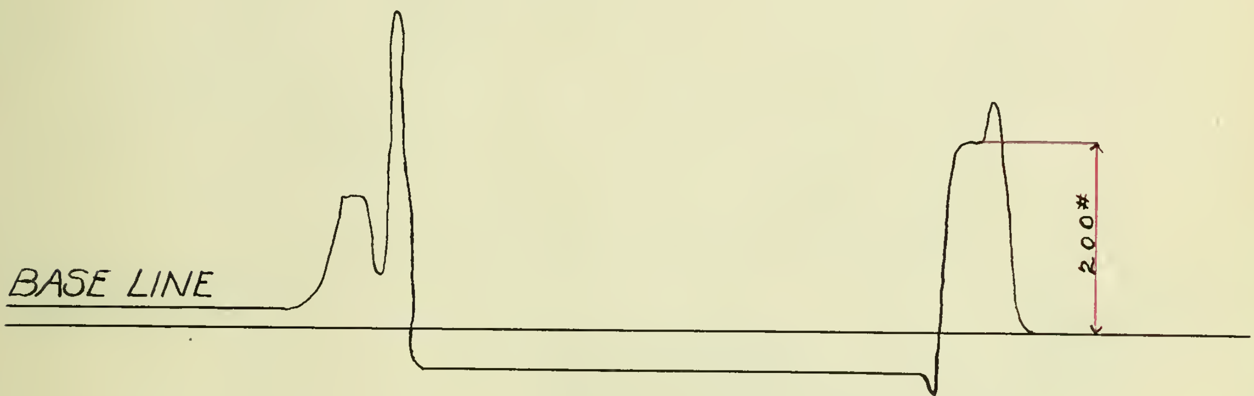
DIAGRAM

SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 3 FT. PER SEC.

CLOSURE AFTER IMPULSE PASSES 2ND VALVE

180 FT. FROM VALVE (a).



180 FT. FROM VALVE (b).

240 FT. FROM VALVE.

DIAGRAM

SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 5 FT. PER SEC.

CLOSURE AFTER IMPULSE PASSES 2ND VALVE

AT VALVE

60 FT. FROM VALVE.

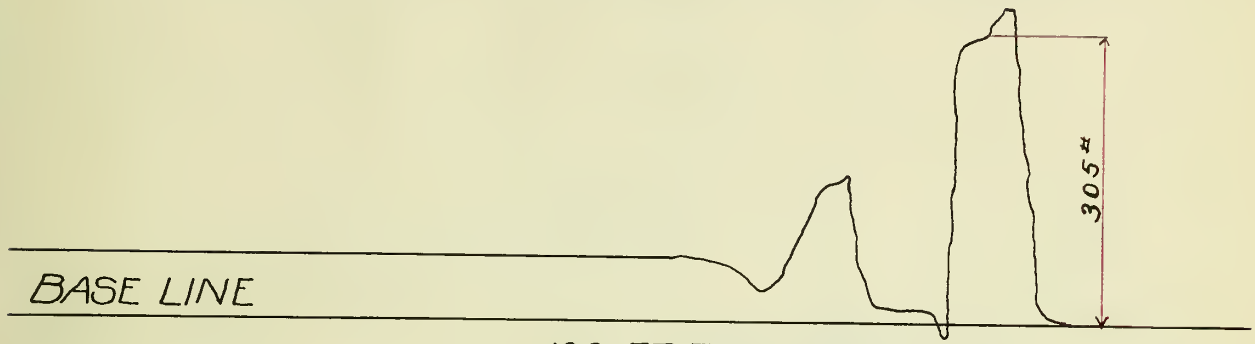
120 FT. FROM VALVE.

DIAGRAM

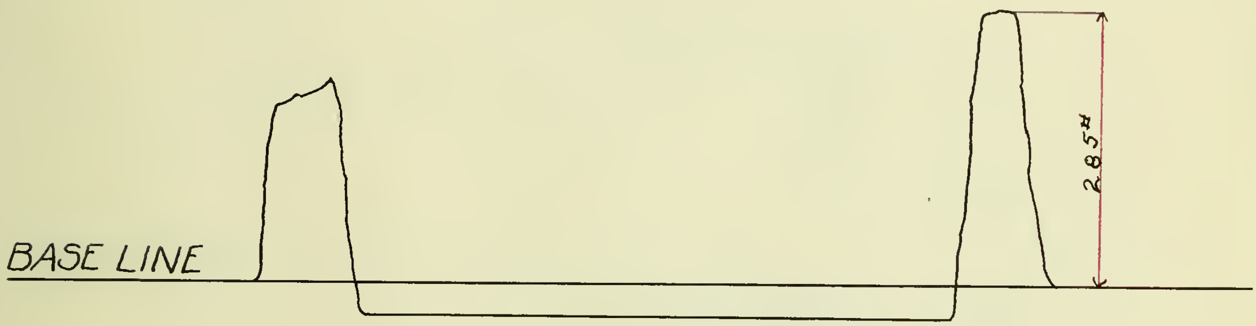
SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 5 FT. PER SEC.

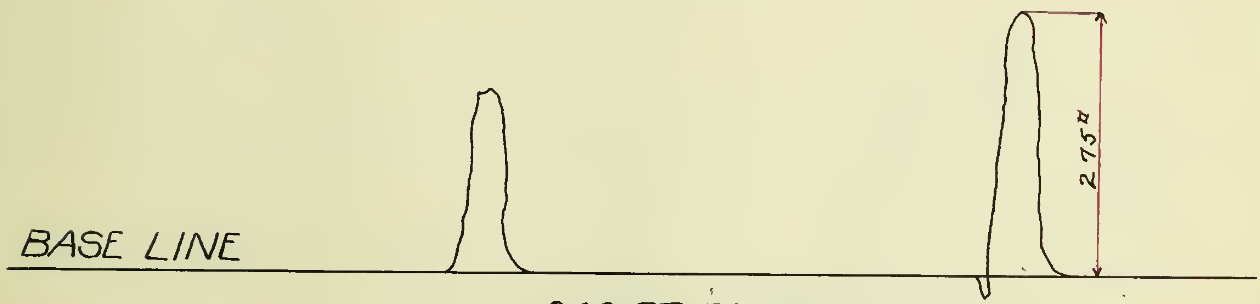
CLOSURE AFTER IMPULSE PASSES 2ND VALVE



180 FT. FROM VALVE (a)



180 FT. FROM VALVE (b)



240 FT. FROM VALVE.

DIAGRAM

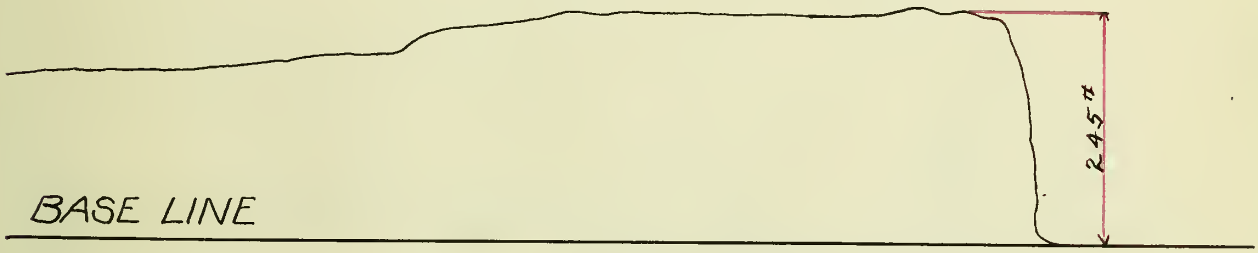
SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 5 FT. PER SEC.

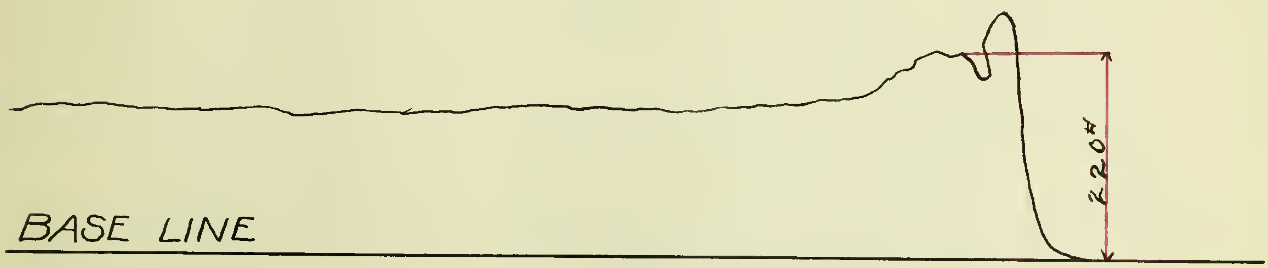
CLOSURE AFTER IMPULSE PASSES 2ND VALVE ON RETURN FROM STANDPIPE.

BASE LINE

AT VALVE



60 FT. FROM VALVE



120 FT. FROM VALVE.

DIAGRAM

SHOWING PULSATIONS

300 FT. PIPE VELOCITY = 5 FT. PER SEC.

CLOSURE AFTER IMPULSE PASSES 2ND VALVE ON RETURN FROM STANDPIPE.

180 FT. FROM VALVE (a).

180 FT. FROM VALVE (b).

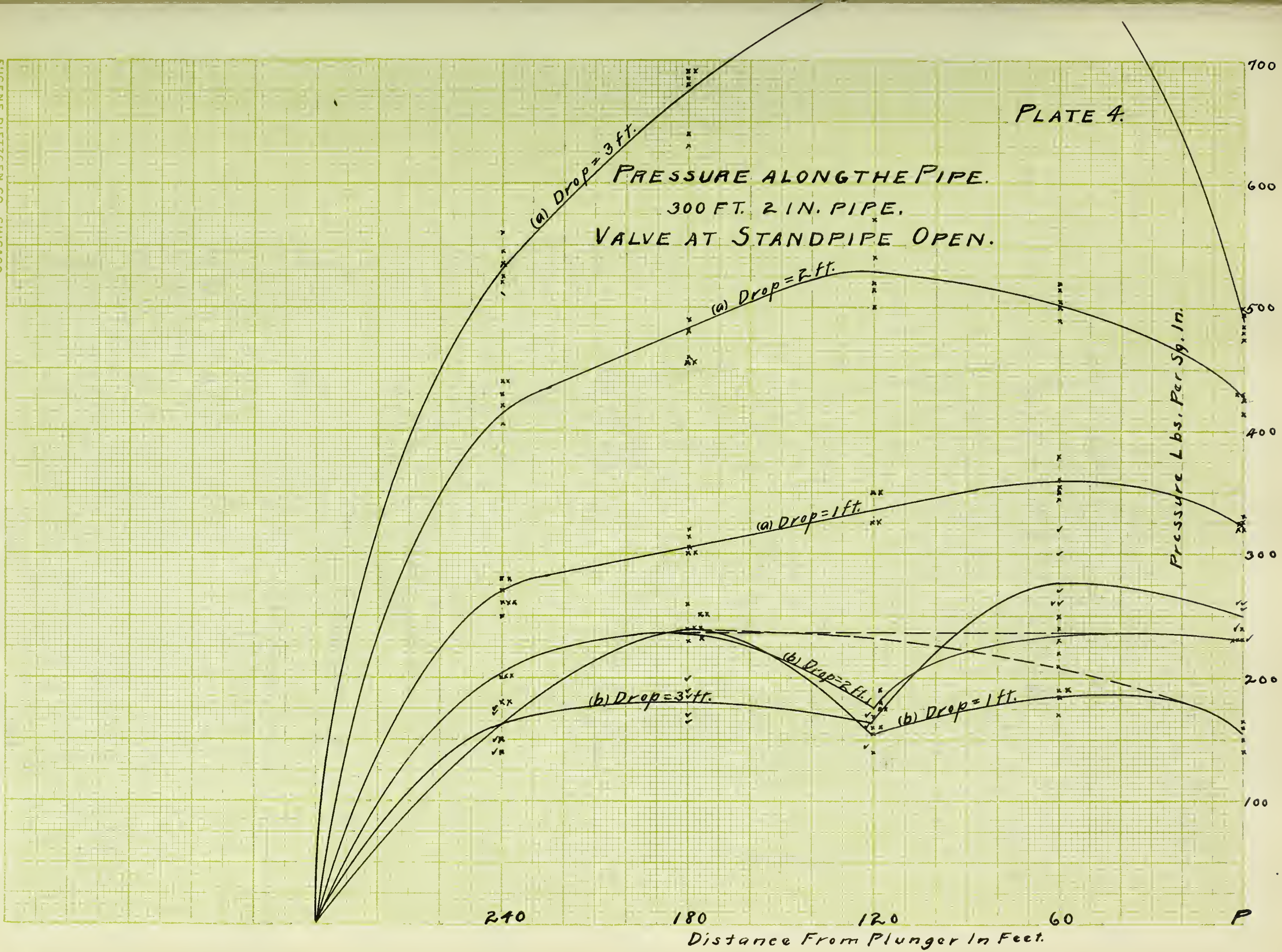
240 FT. FROM VALVE.

Pendulum and Plunger Experiments.

The fall of the pendulum striking the plunger was varied, 1, 2, and 3 feet. Two curves are given for each drop. The points on the curves (a) were obtained by measuring the highest point on the indicator diagram, while the points on the curves (b) were measured from a check in the descent of the indicator pencil after its first upward impulse. The high point is due to the inertia of the indicator pencil carrying it beyond the point of real pressure. The pressures shown by curves (a are greatly excessive, while the pressures shown by the curves (b) vary above or below the real pressures. However, it will be assumed that the curves (b) representing the lower pressures, are correct.

1. Standpipe Valve Open.

The curves on plate 4 give the pressures along the pipe. It will be noticed that except at 120 feet from the plunger, the pressures increase somewhat until 180 feet is reach, from which point they decrease rapidly. It is the writer's opinion that if the



EUGENE DIETZGEN CO., CHICAGO.

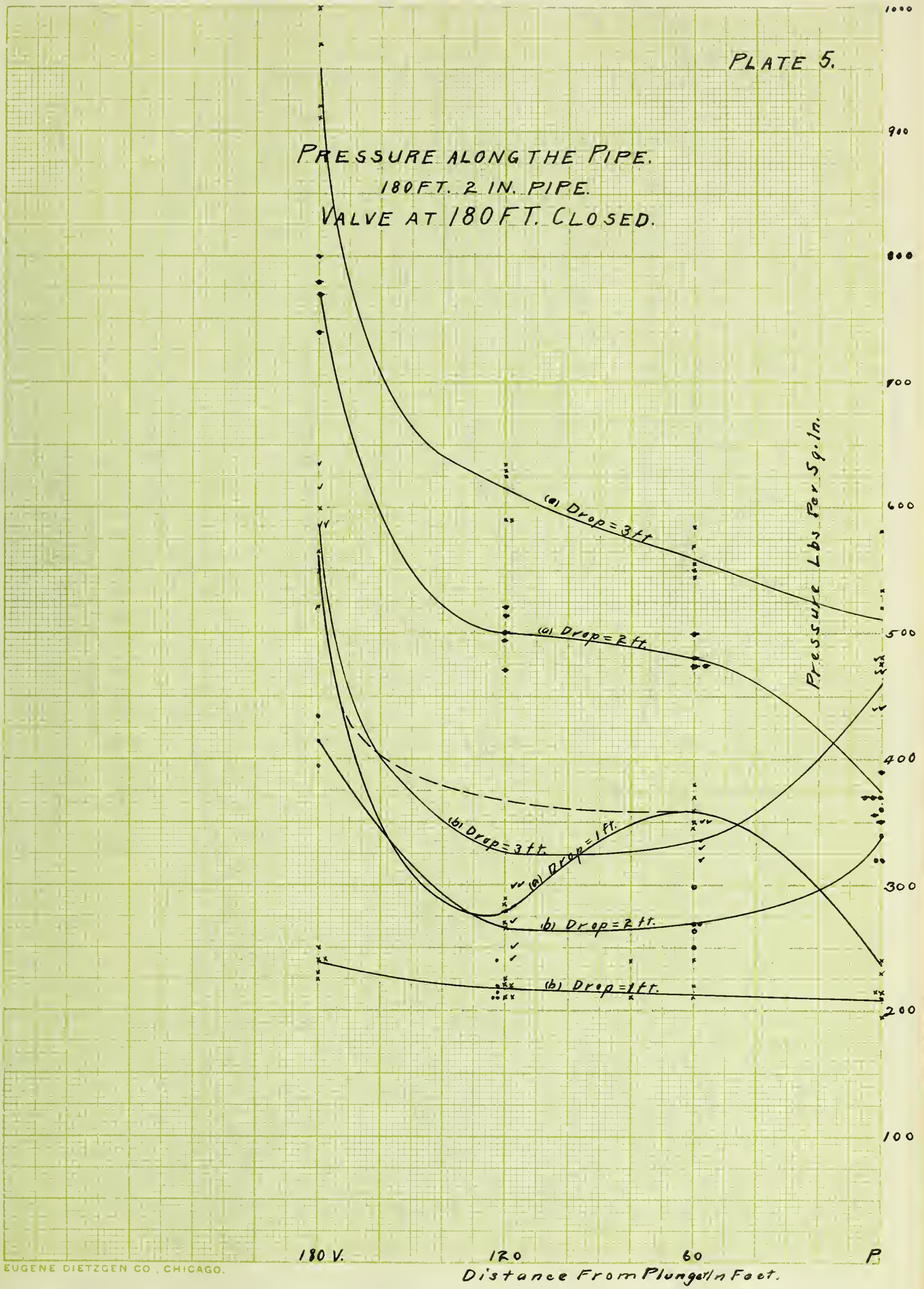
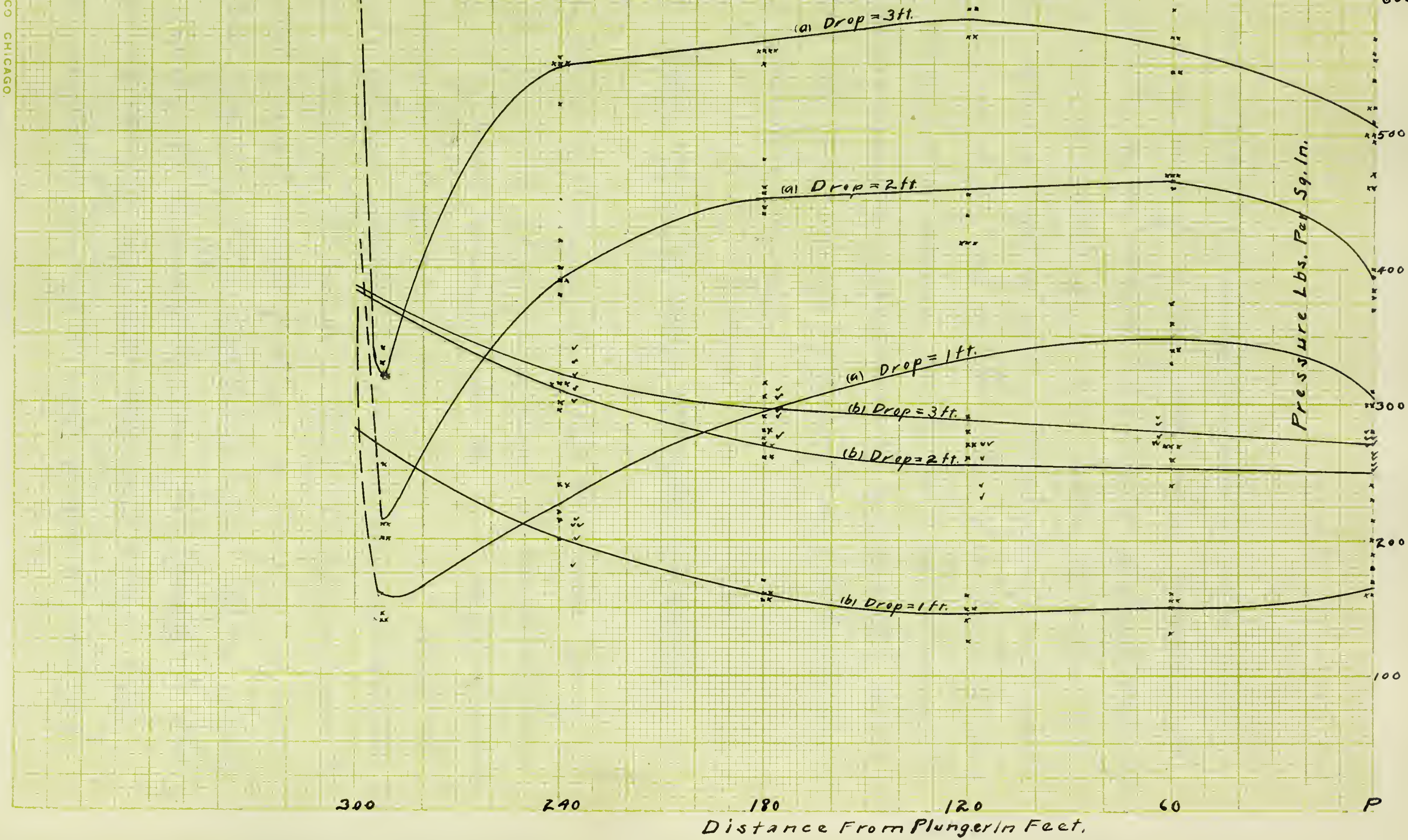


PLATE 5.
PRESSURE ALONG THE PIPE.
180 FT. 2 IN. PIPE.
VALVE AT 180 FT. CLOSED.
(a) Drop = 3 ft.
(a) Drop = 2 ft.
(b) Drop = 3 ft.
(a) Drop = 1 ft.
(b) Drop = 2 ft.
(b) Drop = 1 ft.
Pressure Lbs Per Sq. In.
1000
900
800
700
600
500
400
300
200
100
180 V.
120
60
P.
Distance From Plunger In Feet.
EUGENE DIETZGEN CO., CHICAGO.

PLATE 6.

PRESSURE ALONG THE PIPE.
300 FT. 2 IN. PIPE.
VALVE AT STANDPIPE CLOSED.



if the true readings could be obtained, the curve would be very nearly a horizontal line to about the 240 ft. point, after which it would fall off rapidly. Such a curve would in some respects resemble the curve obtained by checking the velocity of water flowing in a pipe. No explanation has been found for the drop in pressure at 120 ft., but it may be due to the connections between the indicator and the pipe. The pressures appeared as pulsations at decreasing intervals.

2. Valve, 180 Feet from Plunger, and Closed.

In these experiments, the pipe was only 180 feet long, and it was closed at the end by a valve. Two curves (a) and (b) for the two different points of the indicator diagram, are given on plate 5. Except for the 1 ft. drop, the pressures increase from the center towards the ends. This increase was to be expected, as the valve forms a dead-end, and it has been observed by experimenters that a dead-end increases the pressure, due probably to the impulse striking against the rigid body. The secondary impulse was generally present, but it

was very small. When the pendulum struck the plunger, it recoiled as though it had struck a stiff spring.

3. Standpipe Valve Closed.

A 300-foot length of pipe was used in these experiments, and the valve at the standpipe was closed. The curves, plate 6, for these experiments are of the same general nature as those of the previous experiments. However, it will be seen that the changes in the pressures along the pipe are more gradual, because the same amount of energy is expended, and it is distributed through a longer column of water. For the same reason, the pressures will be less.

Work of Compression.

A comparison of the work of compression and the energy in the pendulum will be of interest, and will give an idea of the real pressure. Let λ equal the amount of compression for

a length x, then $\lambda = \frac{Sx}{E}$, where S equals the unit pressure and is equal to P_1 and E the modulus of elasticity of the water. When $S = 100$ pounds and $E = 300{,}000$, $\lambda = \frac{100x}{300{,}000}$ = the compression in a column x long. For a column 20 feet long $\lambda = \frac{100 \times 12 \times 20}{300{,}000} = .0816$ inches, if the pressure is considered uniform for this distance.

Taking the average pressure for each 20-foot length of pipe from the curves on plates 4, 5, and 6, the approximate amount of compression for each 20 feet is found. Beginning at the plunger and adding these amounts, the sum equals the total compression of the column, or the movement of the plunger after the blow from the pendulum.

In computing the work of compression, it was considered that the energy of the plunger was not only expended in compressing the water, but also in giving velocity to the water. This is the condition for longitudinal impact. The formula $K = (P + \frac{1}{3}W)\frac{V^2}{2g}$ is given in Merriman's "Mechanics of Materials", page 226, where K is the work stored up in the impinging body and the body under impact, P the weight of the impinging body, W the weight of the body under impact, and

V the common velocity of the two bodies after impact. Applying this formula to the case in hand, P will be represented by the pressure in the pipe, W by the weight of water, and the quantity $\frac{V^2}{2g}$, which is distance moved through, by λ. Neglecting the quantity $\frac{1}{3} W \frac{V^2}{2g}$, which is small in this case, we have for the work of compression in a given length of pipe, $K = P \times \lambda \times$ area of the pipe. The following tables give the values as computed by the above formula.

Calculated compression, movement, and work.

300 ft. pipe Drop = 1 Ft.

Average Pressure	Dist. from Plunger. ft.	Comp. in 20 ft.	Total Movem'T.	Work of Compr in. lbs.
153	0	.000	.000	0.00
165	20	.132	.132	75.1
183	40	.146	.278	91.9
193	60	.154	.432	102.0
189	80	.157	.584	99.1
177	100	.141	.725	85.6
163	120	130	.855	72.9
174	140	.139	.994	83.3
205	160	.164	1.158	115.4
219	180	.176	1.334	132.9
218	200	.174	1.508	130.2
201	220	.161	1.669	111.2
176	240	.141	1.810	85.4
143	280	.114	1.924	56.2
100	280	.080	2.004	27.4
38	300	.030	2.034	3.8
		Total work		1272.5

Energy of Pendulum = 1128 in. lbs
Movement of Plunger = 2.2 in.

300 Ft. Pipe. Drop = 2 Ft.

Average Pressure	Dist. from Plunger	Comp. in 20 ft.	Total Movem't	Work of Compr.
230	0	.000	.000	00.00
231	20	.185	.185	149.1
234	40	.187	.372	153.1
235	60	.188	.560	153.9
232	80	.185	.745	140.0
219	100	.175	.920	133.5
192	120	.154	1.074	103.5
192	140	.153	1.227	102.6
220	160	.176	1.403	134.6
232	180	.186	1.589	150.1
234	200	.187	1.776	152.0
227	220	.182	1.958	143.9
214	240	.171	2.129	127.6
188	260	.150	2.279	98.5
148	280	.118	2.397	61.0
63	300	.050	2.447	10.7
	Total Work			1823.1

Energy of Pendulum = 2256 in. lbs.
Movement of Plunger = 2.7 in.

The work of compression was not computed for the 3-foot drop, because the pressures shown on the curve are very much too small. The average movement of the plunger was 3.3 inches. The energy in the pendulum was 3384 inch pounds.

Valve at 180 Ft. and Closed.

180 Ft. Pipe. Drop = 1 Ft.

Average Pressure	Dist. from Plunger	Comp. in 20 ft.	Total Movem't.	Work of Compr.
206	0	.000	.000	0.00
207	20	.165	.165	117.1
208	40	.166	.331	118.8
210	60	.168	.499	121.2
211	80	.169	.668	122.9
213	100	.170	.838	124.6
215	120	.172	1.010	127.2
219	140	.175	1.185	131.8
225	160	.180	1.365	139.3
233	180	.186	1.551	148.8
			Total Work	1151.7

Energy of Pendulum = 1128 in. lbs
Movement of Plunger = 1.55 in.

180 Ft. Pipe. Drop = 2 Ft.

Average Pressur	Dist. from Plunger	Comp. in 20 ft.	Total Move m't	Work of Compr.
342	0	.000	.000	0.00
326	20	.260	.260	291.2
297	40	.238	.498	242.6
279	60	.223	.721	213.6
267	80	.212	.933	194.8
262	100	.209	1.142	188.0
261	120	.209	1.351	188.0
271	140	.217	1.568	202.4
296	160	.237	1.805	241.2
358	180	.286	2.091	352.4
			Total Work	2114.2

Energy of Pendulum = 2256 in. lbs.
Movement of Plunger = 2.2 in.

180 Ft. Pipe. Drop = 3 Ft.

Average Pressure	Dist. from Plunger	Comp. in. 20 ft.	Total Movem't.	Work of Compr.
460	0	.000	.000	000
429	20	.343	.343	505.1
378	40	.302	.645	392.8
348	60	.278	.923	342.4
331	80	.265	1.188	301.6
323	100	.258	1.446	295.2
324	120	.259	1.705	293.6
337	140	.270	1.975	313.2
372	160	.298	2.273	381.5
483	180	.386	2.659	641.9
			Total Work	3467.3

Energy of Pendulum = 3384 in. lbs
Movement of Plunger = 2.8 in.

Standpipe Valve Closed.

300 Ft. Pipe. Drop 1 Ft.

Average Pressure	Dist. from Plunger	Compr. in 20 ft.	Total. Movem't.	Work of Compr.
168	0	.000	.000	000
164	20	.131	.131	73.1
162	40	.129	.260	71.7
156	60	.125	.385	67.4
149	80	.119	.504	61.1
147	100	.117	.621	59.1
144	120	.115	.736	57.2
146	140	.117	.853	58.7
150	160	.120	.973	61.9
156	180	.125	1.098	67.1
166	200	.133	1.231	76.0
179	220	.143	1.674	87.8
194	240	.155	1.829	103.4
206	260	.162	1.991	114.6
236	280	.204	2.195	162.0
275	300	.220	2.415	212.6
		Total	Work	1333.7

Energy of Pendulum = 1128 in lbs.
Movement of Plunger = 1.8 inches.

The work of compression was not computed for the two-foot drop, because the pressures shown on the curve are excessive. The average movement of the plunger was 2.3 inches. The energy of the pendulum was 2256 inch pounds.

300 Ft. Pipe. Drop=3Ft.

Average Pressure	Dist. from Plunger	Compr. in 20ft.	Total Movem't.	Work of Compr.
268	0	.000	.000	000
269	20	.215	.215	199.0
272	40	.217	.432	201.3
275	60	.220	.652	208.4
279	80	.223	.875	214.0
282	100	.225	1.100	217.9
285	120	.228	1.328	224.0
289	140	.231	1.559	229.6
292	160	.233	1.792	231.6
294	180	.235	2.027	236.4
298	200	.239	2.266	245.6
306	220	.245	2.511	257.9
315	240	.252	2.763	273.0
326	260	.261	3.024	292.6
340	280	.272	3.296	317.6
355	300	.284	3.580	346.4
			Total Work.	3696.3

Energy of Pendulum = 3384 in. lbs
Movement of Plunger = 2.9 inches.

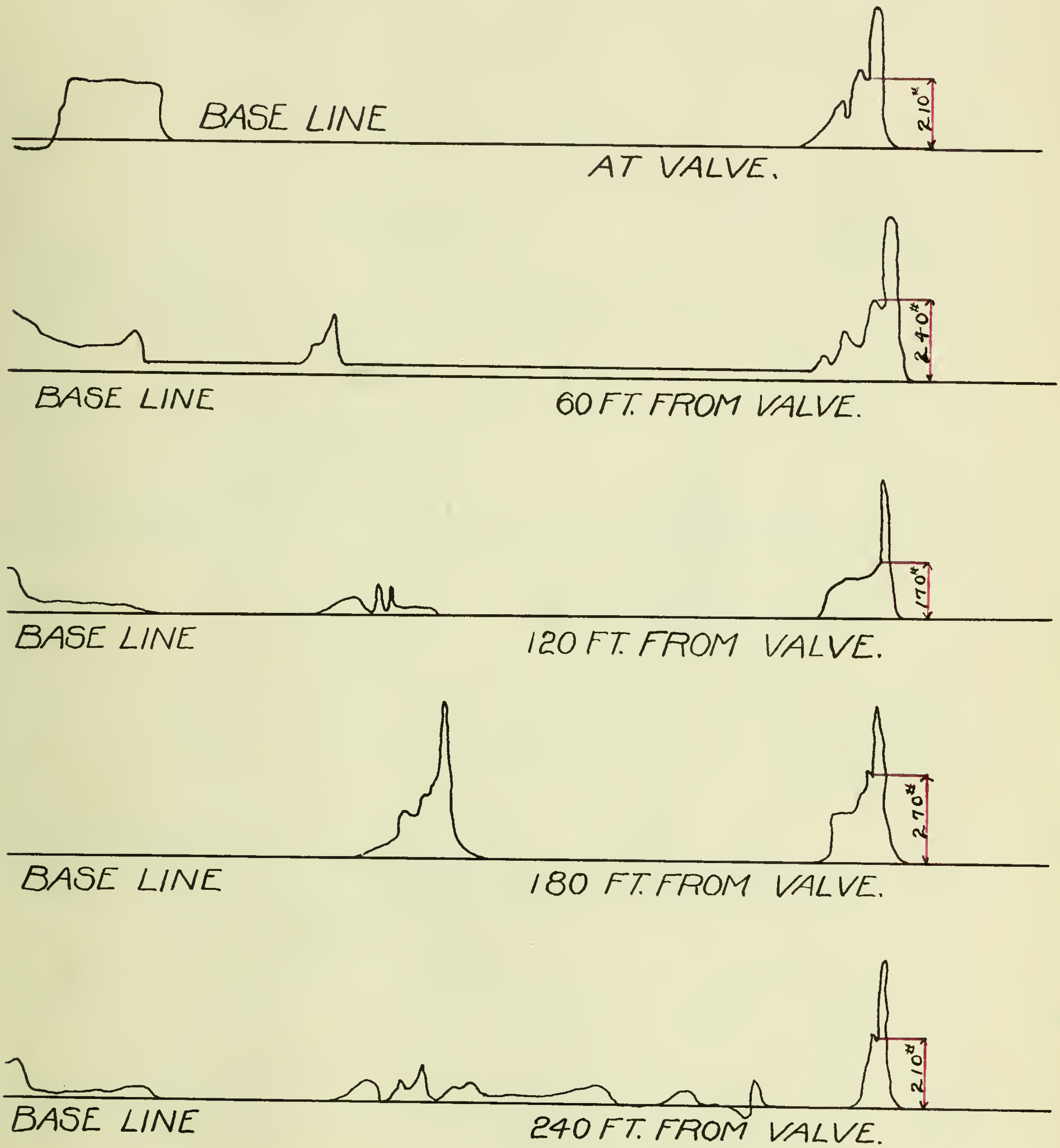
The values given in these tables are only relative values, and rang both above and below the true values. However, they show the close relation existing between the energy in the plunger, and the work of compression.

DIAGRAM

SHOWING PULSATIONS

300 PIPE 2 FT. DROP.

STAND-PIPE VALVE OPEN 50 FT. HEAD.

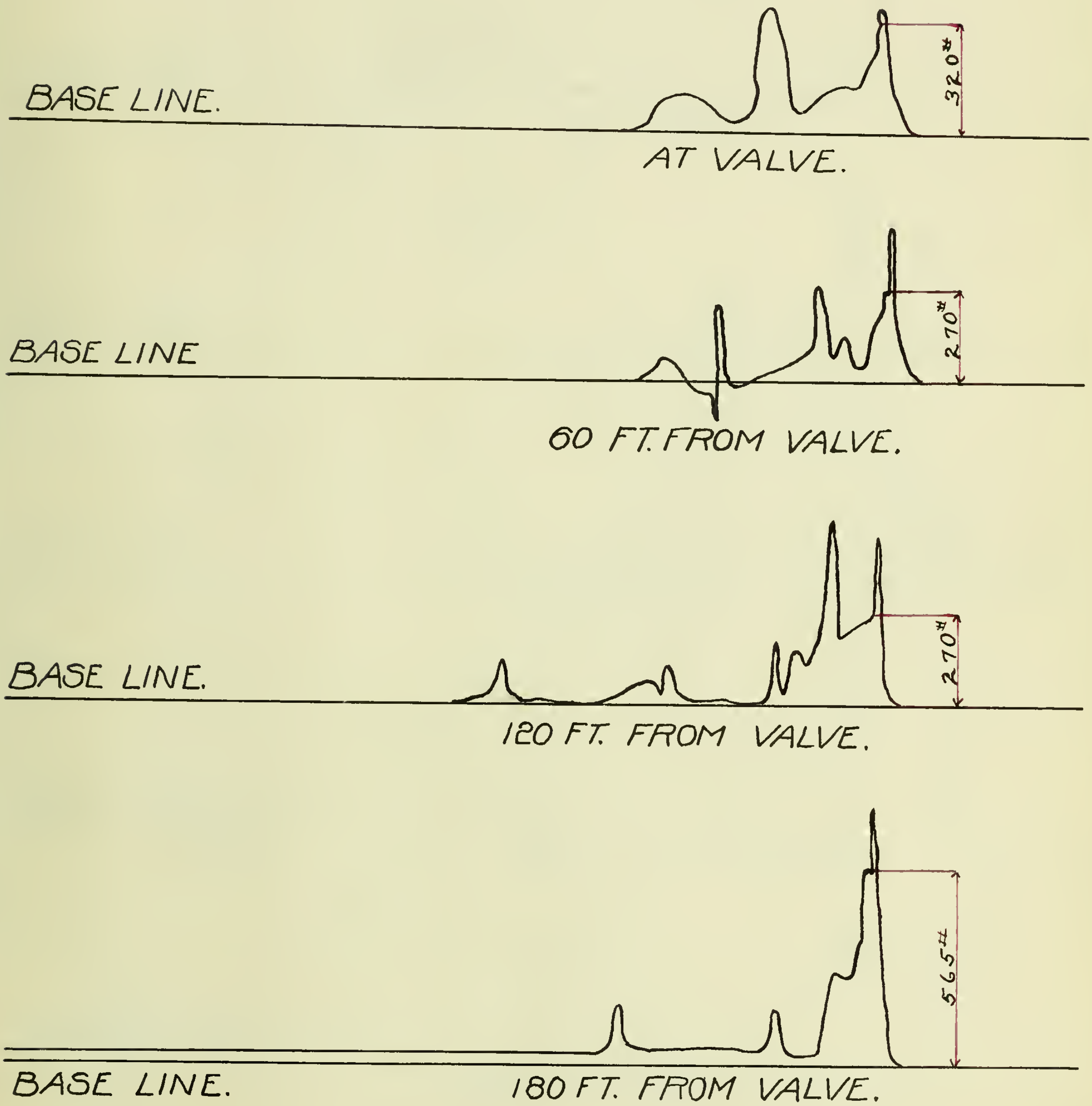


DIAGRAM

SHOWING PULSATIONS

180 FT. PIPE 2 FT. FALL.

VALVE AT 180 FT. AND CLOSED.

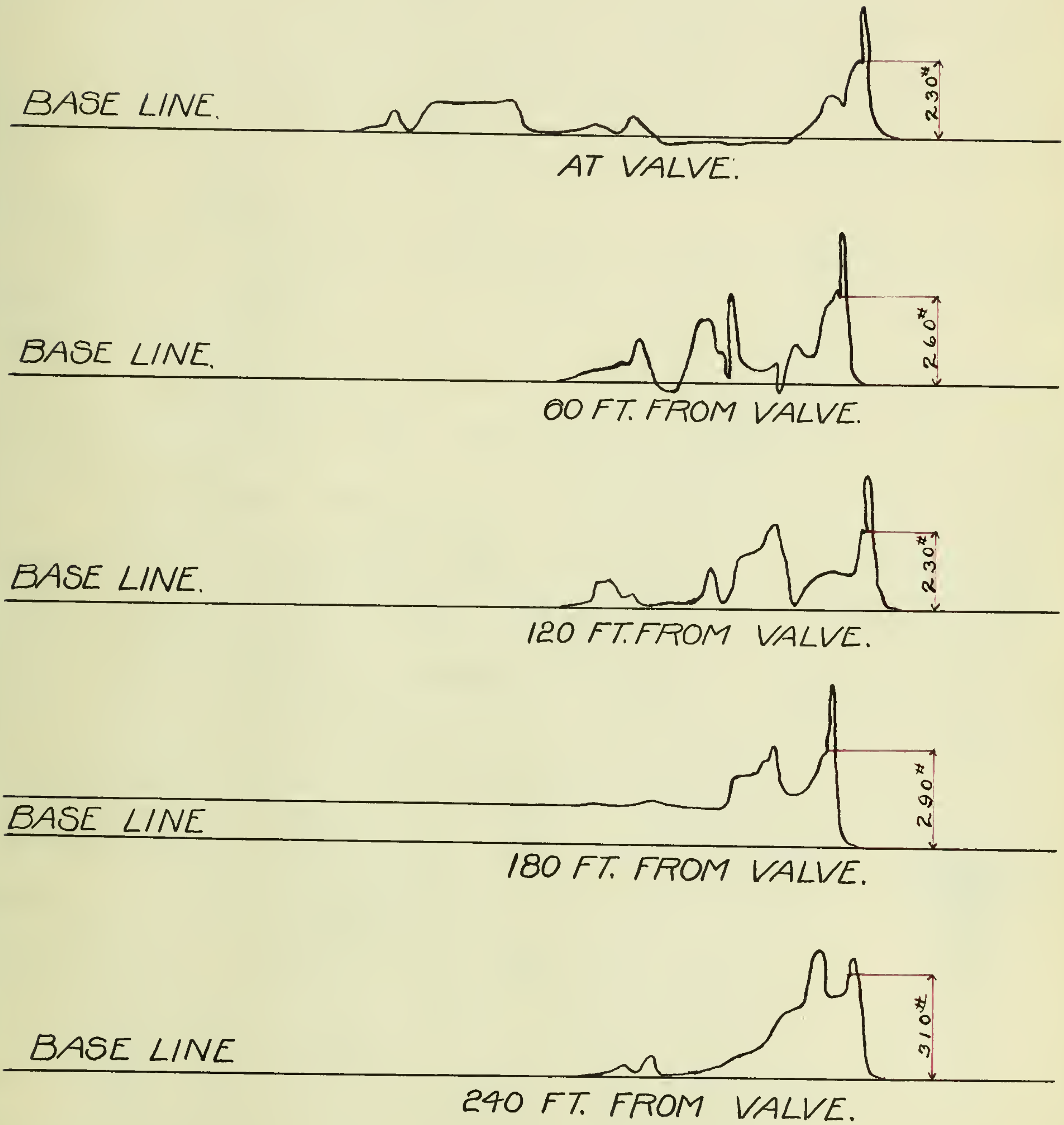


DIAGRAM

SHOWING PULSATIONS

300 PIPE 2 FT. FALL.

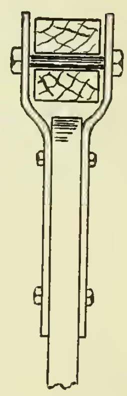
STAND-PIPE VALVE CLOSED.



Suggestions Regarding Apparatus.

The apparatus used in these experiments was in some respects rather crude and defective. Several improvements have suggested themselves to the writer during the progress of the experiments, and it was thought best to note these for future experimenting.

Referring to the sketches of the device for closing the two valves, page 16, it will be seen that the bolts working in the slots of the connecting bar are fastened to the side of the valve handles. This arrangement causes a side-draft on the valve handles, and retards the rapidity and uniformity of closure, and is likely to cause a binding of the bolts in the slot, especially as the valves are not in a direct line. To obviate this effect, the valves should first be placed in a direct line; then two stiff steel straps should be firmly bolted to each valve handle as shown, so that the connecting bar may move in a line directly over the handles. It should also be seen to that the valve handles



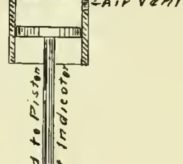
are secured firmly to the valves.

To secure the best results, the valves should be closed not slower than .1 second, and better .08. It was, however, found rather difficult to close the valves uniformly, and at the rate for which the stops on the connecting bar were set. Consequently, it was difficult to secure uniform results. It is, therefore, necessary to employ some mechanical means to secure a uniform and constant rate of closure. Its action must be positive and quick. A spring would serve the purpose were it not for the length required to obtain a travel of the connecting bar in some cases amounting to 22 inches. After securing such a means of closure, two electro-magnets, one for each valve, should be used for timing the closure of the valves, so that a check may be had upon the time of closing of the second valve, in case there should be some variation in the rate of closing.

The experiments with the pendulum and plunger were unsatisfactory in that it was very difficult to ascertain the point on the indicator diagram, which gave the correct pressures. It is, of course, impossible to overcome wholly,

the inertia of the indicator arm, but its effect may be modified and reduced. A sufficient increase in the speed of the recording device would make any check in the descent of the indicator point more marked, and so perhaps indicate the point of real pressure; or a lighter spring of such a length that its travel corresponding to that of a heavier spring, would be within its capacity, would serve the same purpose. A combination of the two would be still better. This method, however, does not overcome the effect of the inertia, and consequently does not entirely remove the chance for error.

Prof. A. N. Talbot suggested the use of a dash-pot connected directly to the piston of the indicator. It seems that such an arrangement would secure the desired result. The accompanying sketch shows the method of operation. The air vent is small and does not allow a rapid escape of air. Consequently the air will be compressed on the upward movement of the piston, and the inertia of the indicator overcome. On the downward move-



ment, there would be a tendency to form a vacuum, but this is obviated by the opening of the air inlet, and so allowing a free downward movement. The parts should be made light, and it might be best to regulate the area of the air vent. The indicator would have to be calibrated for this device.

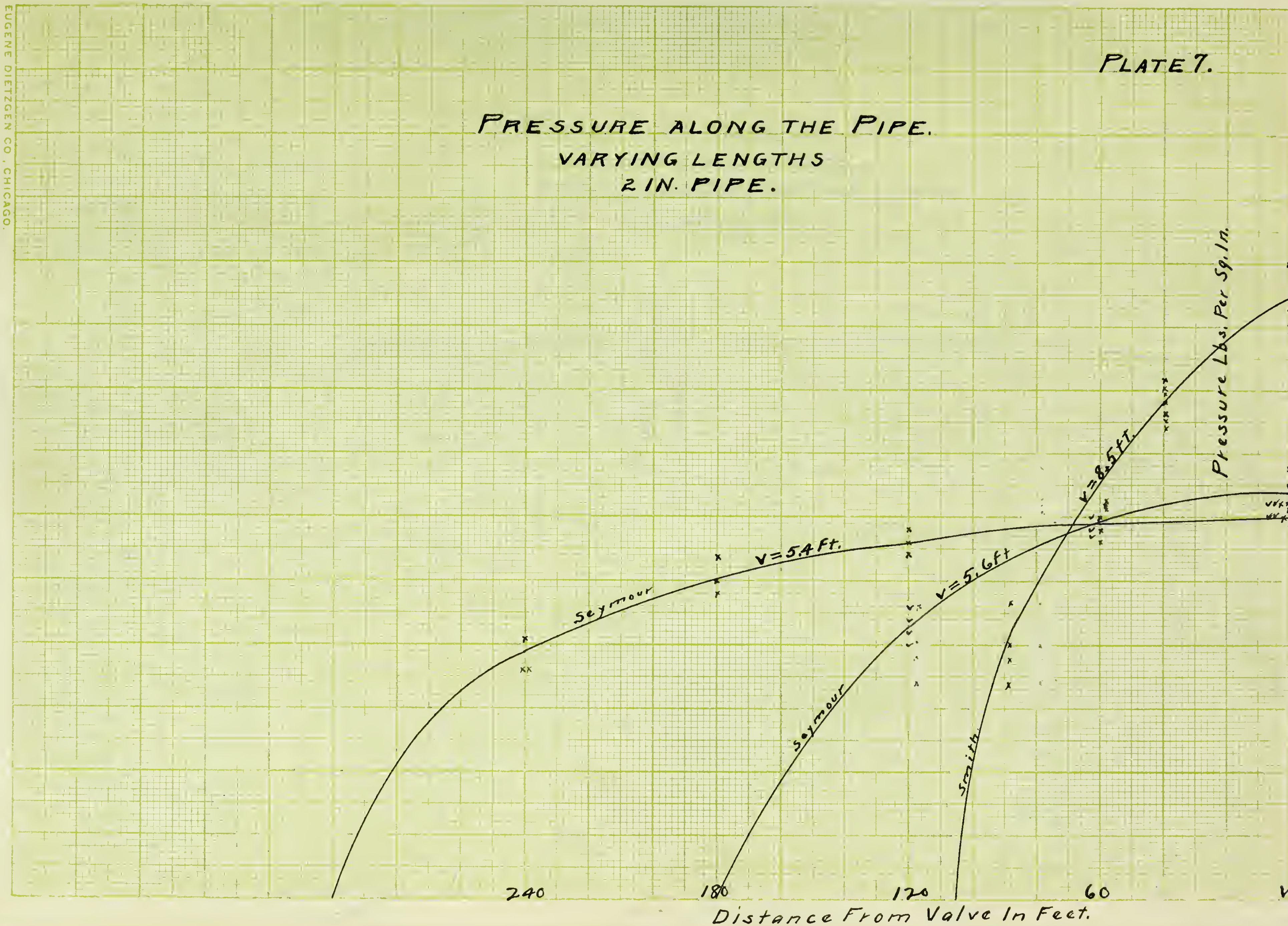
A weight dropped on the plunger would have some advantages over a pendulum in that it could be more easily controlled. For the same amount of energy, it would be nearer the plunger and a more direct blow could be struck the plunger. Since the blow is downward, there is less likelihood of jarring the indicators.

Discussion of Experimental Data.

Mr. Smith and Mr. Seymour in their theses on water hammer arrived at the conclusion that the pressures along the pipe decrease from the valve to the free end nearly as the square root of the distance. The writer for various reasons does not believe this to be true except for certain conditions stated below. Plates 7 and 8 are curves for pressures along the pipe, taken from the theses referred, and from Prof. Joukowsky's experiments at Moscow. A marked difference will be noted between the curves from the two theses and those from Prof. Joukowsky's experiments. The pressures in the former decrease at an increasing rate from the valve end towards the free end, while in the latter, the pressures are uniform until close to the free end, when they decrease rapidly. As both sets of experiments must be given due weight, it would appear that the phenomenon of water hammer as observed by Mr. Smith and Mr. Seymour, is but a phase occurring at the end of a long line of pipe, or a phase peculiar to short lengths of pipe. Such a view must be correct, or otherwise the disparity could not be accounted for. It will also be noticed that the pressures for a 300-foot pipe do not decrease very much until within a short distance of the standpipe. This view is further strengthened by a reference to plate 1. There the pressure on the far side of the valve is uniform to within a short distance of the free end, and again the

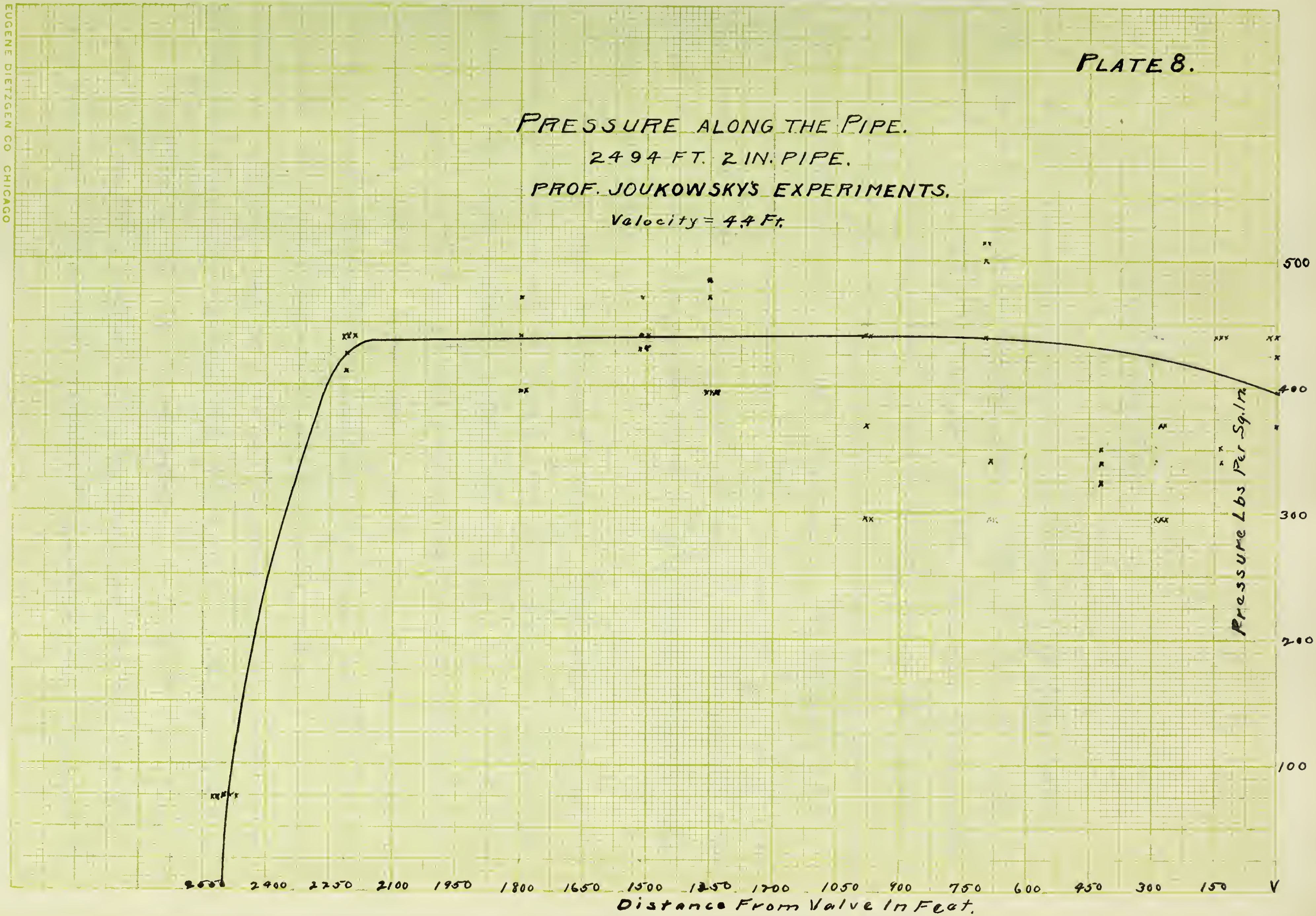
same form of curve is noted in the plunger experiments plate 4. From these curves, the writer is led to believe that even for short lengths of pipe, the pressure should be more uniform than as shown on plates 7. Furthermore, it is peculiar that if this is not a phase pertaining to short lengths of pipe, the function representing the decrease in pressure should vary with a change in length, when the pressures at the valve are nearly equal for equal velocities.

PLATE 7.



PRESSURE ALONG THE PIPE.
VARYING LENGTHS
2 IN. PIPE.
Pressure Lbs. Per Sq. In.
500
400
300
200
100
V=8.5 ft.
V=5.4 Ft.
V=5.6 ft
Seymour
Seymour
Smith
240
180
120
60
V
Distance From Valve In Feet.

PLATE 8.


PRESSURE ALONG THE PIPE.
2494 FT. 2 IN. PIPE.
PROF. JOUKOWSKY'S EXPERIMENTS.
Valocity = 4.4 Ft.
Pressure Lbs Per Sq. In.
500
400
300
200
100
2400
2250
2100
1950
1800
1650
1500
1050
900
750
600
450
300
150
V
Distance From Valve In Feet.

Summary.

For simultaneous closure of the valves; the pressure decreases from the first valve to the second; on the far side of the second valve, the pressure increases markedly over the pressure at the first, and it continues uniform until close to the free end. Between the two valves, there are two impulses, the secondary impulse, however, being very small. Beyond the second valve, there are several successive impulses at decreasing intervals.

The curves obtained when the second valve is closed at such a time as to confine the water between the two valves after the impulse has passed, though not uniform, indicate that the pressures between the two valves are sustained and uniform, and are probably somewhat higher at the mid-points. On the far side of the valve, there is a small increase in pressure, but it drops off almost in a straight line towards the free end. This decrease is thought not to be correct; and that the pressures should rather be uniform as for simultaneous closure. There are several pulsations beyond the

valve at decreasing intervals.

When the valves are closed so as to confine the impulse after it has traveled to the standpipe and back again, there is generally a sustained pressure between the two valves. It is nearly uniform increasing somewhat towards the mid-points. Beyond the second valve, there is a small drop in the pressure, but it increases towards the 240-foot point and then decreases as for simultaneous closure. The pulsations beyond the second valve are as for the two previous cases. The pressures do not appear to increase directly with an increase in velocity.

The pressures resulting from the impact of the plunger increased with some function of the energy in the pendulum, modified by the length of pipe, the condition of the end of the pipe, and the expansion of the pipe.

With the standpipe valve open, the pressures are generally uniform along the pipe until close to the free end, when they decrease rapidly. The pressure is evidenced by several successive shocks at decreasing intervals.

When the standpipe valve or the intermediate valve was closed, the pressures showed a

marked increase at the valve, and generally the lowest pressures were found near the mid-point of the curve. This increase of pressure at the ends was less marked for longer pipe, since the energy was distributed over a greater length, and for the same reason, the pressures were greater for the same amount of energy in a short than in a long pipe.